Andrew Langlee.

FUEL ECONOMY
IN
BOILER ROOMS

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A DEVELOPMENT OF
FUEL ECONOMY AND CO_2 RECORDERS
PUBLISHED IN THE
ENGINEERS' STUDY COURSE FROM POWER

IN TWO PARTS

Part 1: FUEL ECONOMY AND CO_2 RECORDERS

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Part ii: FUEL ECONOMY IN BOILER ROOMS

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Second Impression

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PREFACE TO SECOND EDITION

This book was originally published under the title of "Fuel Economy and CO_2 Recorders," but in the preparation of the second edition, it was deemed necessary to broaden the scope of the work, and to change the title to "Fuel Economy in Boiler Rooms." The new title is more truly indicative of the contents.

The first edition aimed to give the practical man a sound understanding of the principles of combustion, coal analysis, flue gas analysis, the calculations involved in determining boiler efficiency, etc., etc.

In response to requests from all classes of readers, students, firemen, engineers, factory and mill superintendents, particularly the latter, for an extension of the book to include fuels, firing methods, combustion of coal from the practical standpoint, fuel oil burning, stoker operation, boiler settings, burning low grade fuels and waste gases, ready means of checking boiler and furnace efficiency, etc.—in response to the demands for these, urgent in the last year, the present edition has been brought forth.

The book is not a handbook; it is not intended to treat of design, though correct furnace design is mentioned and illustrated to guide the boiler room crew or superintendent. The furnaces with which men are asked to get efficiency in operation in many plants, fuels considered, are wholly unsuited.

Though intended primarily for the student, the fireman and power plant operating engineer, the consulting engineer will find it useful.

All new matter in this edition was prepared by the undersigned, who encourages constructive criticism and suggestions.

<div align="right">CHARLES H. BROMLEY.</div>

NEW YORK,
May, 1918.

PREFACE TO FIRST EDITION

There is, perhaps, no subject in need of more universal attention among power-plant engineers than that of the economical use of fuel under boilers. Happily the subject is getting such attention more and more as its importance is realized.

The cost of fuel in most plants is between 60 and 70 per cent. of the total cost of power. When it is realized further that due to too much excess air, improper furnace design and, above all, careless and ignorant attendance, as much as twenty-five and more per cent. is needlessly wasted in most plants, the reasons for such activity as is now displayed are manifest.

It may be correctly stated that the average power-plant engineer has had but few persons or papers to point out to him, *in his own language*, the causes of waste in the boiler room. Combustion to him, until recently, meant maintaining a fire hot enough to keep the steam gage indicating the correct pressure. The chemistry of the process and of the means for detecting the degree of perfection of combustion were matters for others to consider—others who were fortunate enough to possess the education to understand the terms and technical "mysteries" dealt with.

When preparing the lessons on combustion which first appeared in the Engineer's Study Course from POWER and which make up the largest part of this book, the aim was to present the subjects treated of in a manner easily understandable to the engineers and firemen who have to do with the final use of the fuel and on whom depend how economically it will be used.

THE AUTHORS.

June, 1914.

CONTENTS

CHAPTER VII

CHAPTER VIII

CHAPTER IX

CHAPTER X

CHAPTER XI

PART II

Fuel Economy in Boiler Rooms

CHAPTER I

CHAPTER II

CHAPTER III

CHAPTER IV

CHAPTER V

CHAPTER VI

CHAPTER VII

CHAPTER VIII

PART I

FUEL ECONOMY AND
CO₂ RECORDERS

CHAPTER I

PRINCIPLES OF COMBUSTION

Many believe that to understand combustion and other matters, such as flue-gas analysis, it is necessary to have a good knowledge of chemistry. This is not so. However, it is easiest as one goes along to have a working idea of a few simple technical terms. Therefore, when you come to paragraphs dealing with dry definitions do not shy around them but wade through. They are there for a purpose and you will be paid for your trouble.

When an engineer talks about combustion he means the burning of such fuels as wood, peat, the various grades of coal, such as lignites, bituminous coals and anthracite; coke, oil, gases and such byproduct fuels as tar, bagasse, which is sugar cane after the sugar has been extracted, spent tan bark, corn and corn cobs, etc.

The principal element in all of these fuels is carbon which, by the way, is one of the most widely distributed elements in nature. The diamond is pure carbon; sugar contains a large proportion of it; coke is almost pure carbon; paper contains carbon, so does ink; plants, trees, etc., are composed largely of carbon, and even the human being has a large percentage of this element in his makeup.

It is now important to know what an element is. Any gas, liquid or solid which cannot be changed by some process or other which causes chemical change, into two or more substances of distinctly separate natures is called an element. On the other hand, a gas, liquid or solid which can be changed is called a com-

TABLE I.—COMBUSTION DATA

Col. 1	Col. 2	Col. 3	Col. 4
Name of Element	Symbol of Element	Combining Weight	Combustion Formula
Carbon	C	12	$C + O = CO$ $C + 2O = CO_2$ $CO + O = CO_2$
Hydrogen	H	1	$2H + O = H_2O$
Sulphur	S	32	$S + 2O = SO_2$ $S + 3O = SO_3$
Oxygen	O	16	. . . .
Nitrogen	N	14	. . . .

Col. 5	Col. 6	Col. 7	Col. 8
Compound Formed	Heat Liberated, B.t.u. per lb. of Combustible	Pounds of Oxygen Required per lb. of Combustible	Pounds of Air Required per lb. of Combustible
Carbon Monoxide (Incomplete Combustion)	4,450	$1\frac{1}{3}$	5.76
Carbon Dioxide (Complete Combustion)	14,600	$2\frac{2}{3}$	11.52
Carbon Dioxide	4,350	$\frac{4}{7}$	2.47
Water	62,000	8	34.56
Sulphur Dioxide	. . . .	. . . . .	. . . . .
Sulphur Trioxide	. . . .	. . . . .	. . . . .

pound. To illustrate, pure iron is an element because there is no way to convert it or "break it up" into anything but iron. Iron-rust, however, is a compound, because it is a chemical combination of iron and oxygen and can be divided by a chemical process into iron and oxygen. Water is a compound because it can be divided by intense heat or by electricity into two gases, hydrogen and oxygen.

These two gases, hydrogen and oxygen, are elements because it is impossible to convert them into anything but what they are. They may, however, be reunited chemically with other elements or with compounds and form many different substances. Air is neither an element nor a compound. It is simply a mixture

of elements, mainly oxygen and nitrogen, which may be separated without any chemical change taking place in the mixture.

Although there are thousands of chemical compounds, there are but 79 known elements and nearly half of these are exceedingly rare ones. In the study of combustion, we deal with but the five shown in Table I.

There are two kinds of changes possible in nature, physical changes and chemical changes. A physical change is one that affects the form of a substance but not its character, while a chemical change usually affects both form and character. Two examples of physical changes are the freezing of water to form ice and the heating of water to form steam. While each of these causes the form of the water to change (in one case to a solid; in the other to a vapor) the composition remains exactly the same. If you take a lump of coal and hammer it into a powder you have caused only a physical change, for you have only changed the form of the coal from a lump to a powder which is simply a mass of very small lumps of coal having the same characteristics as the original big lump. But if you burn a lump of coal, it gives off light and heat and the coal changes into an ash and some invisible gases. This is a chemical change because the nature of the substance is completely altered. First you had coal, composed of a large proportion of carbon and small proportions of other substances, such as hydrogen, sulphur, etc. After the change you had left a little ash. The rest of the coal was converted into gases and these passed off into the air.

From this, then, we can describe combustion as a chemical combination of one or a number of combustibles (such as those in Table I), with oxygen (the supporter of combustion), when light and heat are produced.

A fact which is very fortunate from our point of view is this: Chemical elements follow exact laws when they enter into chemical combinations with each other; a fixed weight of one element always combines with a fixed weight of another to form a given compound. Also, a definite amount of heat is always created when a given combination takes place. Thus, when

hydrogen, one of the combustible elements of many fuels, burns, it always requires a fixed amount of oxygen; it always causes a certain amount of heat, and it always results in a certain quantity of the product of its combustion.

CARBON

Carbon in its pure state is a solid, such as graphite and diamonds. As found in solid fuels, part of it is pure and part is in combination with hydrogen forming hydrogen-carbon combinations which, for brevity, are spelled and pronounced hydrocarbons. The pure carbon part of a fuel is usually referred to as "fixed carbon" because when the fuel is heated the hydrocarbons vaporize and pass off in the air, the same as water in a sponge vaporizes and passes off. The pure carbon remains behind, consequently we say it is "fixed."

In liquid fuel, such as crude oil or any of the products of crude oil, such as kerosene and gasoline, carbon is not found in the pure state but is always present in combinations with hydrogen as hydrocarbons. Carbon exists in gaseous fuels, such as natural gas, illuminating gas, blast-furnace gas, etc., but only in combination with either hydrogen or oxygen (principally with hydrogen in the shape of hydrocarbons).

When carbon burns completely, it always requires a certain amount of oxygen, and hence, a certain amount of air, because the oxygen is supplied by the air and the proportion of oxygen found in the air is the same in New York as it is in Punxsutawney or San Francisco; in fact, the proportion remains the same the world over. You may supply more oxygen by supplying more air but the excess will not be used. A given amount of carbon will use (or combine with) only so much oxygen, never any more and never any less.

Did you notice in the beginning of the last paragraph that it was said "when carbon burns completely"? Care was taken to specify complete combustion because carbon will undergo partial or incomplete combustion when conditions are not right for

complete combustion. But this need not worry us, because this incomplete combustion also follows definite laws. A certain amount of carbon incompletely burned will use a certain amount of air every time and will give up a certain amount of heat every time. What the oxygen or air requirement is in each case and what the amount of heat is created will be taken up later. Just now we will talk about some of the other elements.

HYDROGEN

Pure hydrogen is a colorless and odorless gas. It exists in coal in combination with carbon, forming the hydrocarbons mentioned before. These hydrocarbons form the principal part of the volatile matter in coal. When a coal is heated to a certain temperature, certain quantities of vapors or gases are given off, depending on the nature of the coal. With bituminous or "soft" coals, large quantities are given off; with anthracite or "hard" coals only small quantities are given off. These vapors or gases are known as the volatile matter of the coal. Hydrogen is likewise found in a combined state in the liquid fuels. In gaseous fuels it exists in both the free and the combined state.

When hydrogen burns, it burns completely; there is no part or half-way process with it as is the case with carbon. Hydrogen produces intense heat and as a fuel it has great value.

SULPHUR

Sulphur in its pure state is a yellow solid substance which burns very easily and forms a disagreeable smoke. It exists to some extent in practically all coals and fuel oils. It is undesirable in fuel because its heat value is very small and because it tends to form an acid which quickly corrodes the ironwork of flues and chimneys. Sulphur also increases the clinkering properties of the coal. Ordinarily the amount of sulphur found in coal and oil is small, and hence, because its heat value is low, we can easily afford to ignore it in our calculations. It is well to bear

in mind, however, that the less sulphur a fuel contains the more desirable it is.

MOISTURE, ASH, ETC.

In addition to the elements just mentioned, all solid fuels contain water, ash and a few other impurities. The water is usually referred to as moisture. This water cannot be squeezed out like water from a sponge, but it can practically all be dried out from coal simply by heating the coal for a certain length of time. In oil fuel, which also contains moisture, most of the water will settle out when the oil is allowed to stand for a sufficient time.

The amount of moisture which a coal contains depends almost entirely upon the nature of the coal. Some coals are more sponge-like than others; that is, they have greater capacity for holding water than others. The amount of ash or unburnable solid material in coal also varies greatly with the kind of coal, and sometimes the same kind of coal will run very unevenly in this respect. As ash and moisture do not create heat, naturally, the less of these a fuel contains the better it is.

In addition to the ash and moisture, coal contains a few other impurities, principally oxygen and nitrogen. The latter need not worry us in the least because the amount of it is small and it has but slight effect on the results anyhow. The oxygen contained in coal sometimes runs rather large in quantity and hence it is important to know about it, although in our ordinary work in boiler-room economy we can afford to forget about it, and we will, later on, when we "get down to cases." But it is a good idea to get a fair understanding of the whole story so that when we read technical articles and reports we will have some idea of what they are all about.

Even the scientists are not certain as to exactly what form oxygen exists in coal. They are not sure whether it is there as an element, that is, as free or uncombined oxygen; or as a compound with hydrogen in the form of water so tightly mixed up in the coal that no amount of heating, short of burning, will drive it out like ordinary water; or whether it is in the coal in some com-

bination with carbon as carbon dioxide or CO_2. However, it is generally believed, and always assumed that the oxygen exists in the coal as a compound with hydrogen in the form of water. Hence, when an analysis of a coal shows that it contains both oxygen and hydrogen, only part of the hydrogen is considered as available for combustion. The other part is considered as being already combined chemically with the oxygen of the coal in the form of water, H_2O. And, as water is noncombustible, the hydrogen thus combined is useless as fuel. Hence, when you see the term "available hydrogen" in a report of a coal analysis, you will know that it means, not all the hydrogen found in the coal, but only the part which is in excess of the amount required by the oxygen existing in the coal to form water.

AIR

Air is composed of the gases, oxygen and nitrogen, and very small quantities of a few other elements and a few compounds. The oxygen and nitrogen form such a large part of the air (99 per cent. or more) that for all practical purposes they are the only constituents to be considered. As found in the air they are both pure, that is, uncombined with any other elements.

Some people have difficulty in realizing that a gas has weight. They think: "You never could weigh a gas; it is too light; it would not stay on the scale." Consequently, they get confused when they read about pounds of air or pounds of oxygen. It is really easy to weigh a gas if you have a good strong tank or cylinder and a pair of scales that are very sensitive and accurate. Suppose you wished to weigh air, for instance. Although air is not a simple gas, but a mixture of the two gases, oxygen and nitrogen, it makes no difference, the action is the same.

Close the valve on the tank, put the tank on the scale and weigh it. We know that the tank is full of air at atmospheric pressure, because a pressure gage attached to the tank would show zero pressure. Now, connect a good vacuum pump to the tank and pump and pump and pump until the vacuum gage

shows as near 30 in. of vacuum as you can get it to show. Then weigh the tank again. This time the weight will be less, proving that air has weight. If the temperature of the air was 60 deg., if the tank had a capacity of 5 cu. ft. and if it weighed 75 lb. the first time, it would weigh something like 74.618 lb. the second
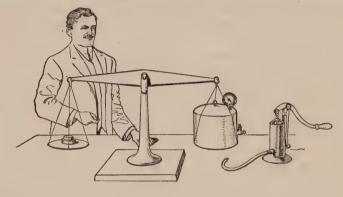
FIG. 1.—Experiment to show that air has weight.

time, showing that the 5 cu. ft. of air pumped out weighed 0.382 lb. or that air at 60 deg. temperature and atmospheric pressure weighs

$$\frac{0.382}{5} = 0.0764 \; lb. \; per \; cubic \; foot.$$

(By the way, it was not necessary to close the valve on the tank for the first weighing. But this is another story to be taken up later.)

You will notice that the temperature of the air when the weighing took place was specified. This was done because air (or any gas) is a very elastic fluid and expands and contracts very easily by being heated and cooled; hence its weight per cubic foot changes with change of temperature; that is, unless it happens to be inclosed in some vessel that will not let it expand. Then it is not the volume nor the weight that changes, but the pressure.

If you think of a gas as a very light fluid it is easy to realize that it has weight just the same as any other fluid, such as water.

By volume, air is composed of 21 per cent. oxygen and 79 per cent. nitrogen. That is, out of every 100 cu. ft. of air, 21 cu. ft. is oxygen and 79 nitrogen. By weight, air is composed of 23.15 per cent. oxygen and 76.85 per cent. nitrogen. That is, out of every 100 lb. of air, 23.15 lb. is oxygen and 76.85 lb. nitrogen.

Measurement of Heat

Now, before we take up combustion, coal analysis and similar subjects, we ought to get a good working idea about how heat is measured because it is necessary to measure the heat generated and absorbed so as to know what results we are getting.

Heat is measured by its intensity or degree and by its amount or quantity. If you lighted an ordinary match and held it so the flame struck the business end of a quick-acting thermometer that could stand the treatment, the thermometer would indicate a certain temperature, let us say 400 deg. Then, if you lighted two matches and held them so that both flames struck the thermometer it might astonish you when you found the thermometer showed only the same temperature as before. You could easily see that there was twice as much flame and it stands to reason that there was twice as much heat because you were burning two matches instead of one and two matches have twice as much wood as one. Then, why was not the temperature twice as great? Because the temperature or the intensity of heat depends upon the nature of the fuel and the way it is burned while the amount burned determines the quantity of heat created. The fire under a 50-hp. boiler may be just as "hot," the temperature may be just as high, as the one under a 500-hp. boiler, yet it does not do as much work, that is, heat as much water, because it does not burn as much fuel and consequently does not generate as great a quantity of heat.

Now, it is seldom possible to measure the quantity of heat direct, but it is quite easy to calculate the quantity when the

temperature and a few other factors are known. This is true because heat acts according to fixed laws, the same as everything else in this world. And when you once understand those laws it is easy to figure out what will happen when certain conditions prevail.
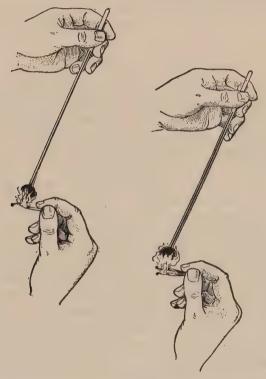
FIG. 2.—Experiment to show that a flame's temperature is independent of its size.

DEFINITION OF B.T.U.

The thermometer measures temperature or heat intensity and the unit of temperature is the degree. According to the Fahrenheit scale, which is the one commonly used in this country,

melting ice has a temperature of 32 deg. and boiling water a temperature of 212 deg.

The unit of heat quantity commonly used is the British thermal unit or the B.t.u., as it is usually written and pronounced. It gets its name from the fact that British scientists established it or used it first and the word thermal means heat or warmth. Another way of expressing it would be, British unit of heat measurement. In fact, we often use the term heat unit when we really mean B.t.u.

One B.t.u. is the quantity of heat required to raise the temperature of 1 lb. of water 1 deg.[1] As a gallon of water weighs $8\frac{1}{3}$ lb., it requires $8\frac{1}{3}$ B.t.u. to raise the temperature of 1 gallon 1 deg., or $16\frac{2}{3}$ B.t.u. to raise the temperature 2 deg., and so on.

Thus, when a given coal is said to have a heat value of 13,800 B.t.u. per pound, it is meant that if all the heat caused by the complete combustion of 1 lb. of that coal could be transmitted to 13,800 lb. of water it would raise the temperature of that water 1 deg. Or, if all the heat could be transmitted to, say 138 lb. of water, it would raise the temperature of that water just 100 deg., because

$$138 \times 100 = 13,800$$

The pounds of water heated multiplied by the number of degrees the temperature has been raised equals the number of B.t.u.

Indeed, the standard method of finding the heat value of a fuel is to burn a small sample of it in a tight steel bomb under water. The heat caused by the burning of the sample is then all absorbed by the water and by multiplying the weight of the

[1] This is only approximately true. It takes a different amount of heat to raise a pound of water from 32 deg. to 33 deg. than it does to raise it from 100 deg. to 101 deg., or from 211 deg. to 212 deg. The B. t.u.,therefore, is variously defined as the amount of heat necessary to raise a pound of water 1 deg. at its temperature of maximum density, about 39 deg.; or, at some arbitrary temperature, 60 or 62 deg., because that is assumed to be the average temperature of the surrounding air when experiments to determine the amount of heat are made; or $\frac{1}{180}$ of the amount of heat required to raise a pound of water from 32 to 212 deg. (the average amount of heat per degree). The latter definition is finding the most favor.

water by its rise in temperature and dividing by the weight of the sample, the heat value of the coal is calculated direct in B.t.u. per pound. Thus, if we burned a small sample weighing one-five-hundredth of a pound in a bomb immersed in 5 lb. of water and if the temperature of that water increased from, say, 70.4 deg. to 75.92 deg., a rise of 5.52 deg., the heat value of the coal would be

$$\frac{5 \times 5.52}{0.002} = 13,800 \ B.t.u. \ per \ pound.$$

Combining Weights of Elements

Whenever a chemical action, such as combustion, takes place, the elements or compounds always combine in fixed proportions by weight. Because of this fact we are able to use Col. 3 in Table I, which gives the combining weights of the various elements. Whenever two or more elements combine they do so either in direct proportion to the numbers shown in Col. 3 or in some multiple of those numbers. The exact manner in which they combine is shown by the formulas in Col. 4. Thus, when carbon combines with other elements it always combines in weights of 12 or some multiple of 12, such as 24, 36, 48, etc., depending on the formula. When oxygen combines it does so in weights of 16 or multiples of 16. And so with all other elements, they combine according to their combining weights or atomic weights as the chemist usually calls them.

Combustion of Carbon

. Carbon has two ways of combining with oxygen. One is called complete combustion and the other incomplete combustion. Whether combustion is complete or incomplete depends upon conditions. If sufficient air is supplied to every particle of the carbon, combustion will be complete; if not, some of the carbon will be only partially burned.

Taking up incomplete combustion first, the formula in Col. 4 is

$$C + O = CO$$

This means that the carbon combines with the oxygen in the proportion by weight of 12 to 16, because those are the combining weights of the two elements. This reduces to 1 to $1\frac{1}{3}$. Hence, for every pound of carbon incompletely burned $1\frac{1}{3}$ lb. of oxygen are required. If 27 lb. of carbon were incompletely burned the amount of oxygen used would be 36 lb., because the proportion of 27 to 36 is the same as 12 to 16 or 1 to $1\frac{1}{3}$. The figuring is just the same for all other quantities of carbon no matter whether the amount is a fraction of an ounce or thousands of tons.

The product of the incomplete combustion of carbon is a gas called carbon monoxide and its chemical symbol is CO.

The name monoxide is one of those built-up words from mono, meaning one or one part, and oxide, meaning the chemical union of oxygen with some other substance. Thus, carbon monoxide means one part of oxygen united with carbon. When the number of parts of the other element is not stated it is always taken as one. Hence, the exact meaning of carbon monoxide is one part of carbon united with one part of oxygen.

To calculate the amount in pounds of the CO formed it is only necessary to add the weight of the carbon burned and the weight of the oxygen required according to the formula; the result is the weight of the carbon monoxide. What the volume of this gas is depends upon the temperature as has been explained.

Thus, if 5 lb. of carbon are incompletely burned the weight of CO formed is

Weight of carbon... 5 lb.
Weight of oxygen required $5 \times 1\frac{1}{3}$............................... $6\frac{2}{3}$ lb.
_____
Weight of carbon monoxide formed............................. $11\frac{2}{3}$ lb.

This carbon monoxide is a combustible gas and if supplied with air so that it can unite with the required amount of oxygen it will burn when heated to its temperature of ignition. Its formula is

$$CO + O = CO_2$$

This means that the CO or carbon monoxide combines with oxygen in the proportion of

$$C + O \text{ to } O$$

$$12 + 16 \text{ to } 16 = 28 \text{ to } 16$$

or 1 to $\frac{16}{28}$, which equals 1 to $\frac{4}{7}$. Thus, for every pound of CO burned $\frac{4}{7}$ of a pound of oxygen is required.

The product of the combustion of CO is a gas called carbon dioxide, which has the chemical symbol CO_2.

The name dioxide is built up in a manner similar to monoxide, the prefix di meaning two or two parts. Thus, carbon dioxide means one part of carbon combined with two parts of oxygen. By "parts" it must be remembered we mean "chemical parts," *i.e.*, combining weights as shown in Table I and explained before. The weight of CO_2 formed by the combustion of CO is found by adding the weight of CO burned to the amount of oxygen required according to the formula. Thus, if 6 lb. of CO were burned to CO_2 the weight of CO_2 formed would be

Weight of CO burned.................................... 6 lb.
Weight of oxygen required 6 × $\frac{4}{7}$........................ $3\frac{3}{7}$ lb.
Weight of carbon dioxide formed......................... $9\frac{3}{7}$ lb.

If sufficient air is supplied in the first place so that each particle of carbon can unite with all the oxygen it desires, complete combustion results, the formula for which follows:

$$C + 2O = CO_2$$

This means that the carbon unites with the oxygen in the proportion of

$$C + 2O = CO_2$$

$$12 + 2 (16) = 44$$

producing $\frac{44}{12} = 3\frac{2}{3}$ lb. of CO_2 for every pound of carbon burned. Every pound of carbon when completely burned requires $\frac{32}{12} = 2\frac{2}{3}$ lb. of oxygen.

COMBUSTION OF HYDROGEN

When carbon is burned, part of it may be burned completely to form CO_2 and the rest may be only partly burned to form CO. This is not true of hydrogen. The hydrogen either burns completely or not at all. Thus, if not enough air is supplied for a given quantity of hydrogen, part of the hydrogen (enough to use up all the oxygen in the air supplied) burns completely and the balance does not burn at all.

The formula for the combustion of hydrogen is

$$2H + O = H_2O$$

According to Table I, Col. 3, the combining weight of hydrogen is 1, that of oxygen 16, the same as in all other cases. Thus, substituting in the formula, we have

$$2H + O = H_2O$$
$$2(1) + 16 = 18$$

It requires then $\frac{16}{2} = 8$ lb. of oxygen for the complete combustion of every pound of hydrogen burned, and the weight of the product formed is $\frac{18}{2} = 9$ lb.

The product formed by the combustion of hydrogen is water (H_2O) in the shape of highly superheated steam. This steam can be condensed just the same as steam made directly from water can be condensed back into water again.

Sulphur burns with oxygen and forms SO_2 in much the same way that carbon burns to form CO_2. The formula is

$$S + 2O = SO_2$$
$$32 + 2(16) = 64$$

From this it will be seen that

$$\frac{32}{32} = 1 \ lb.$$

of oxygen is required for the combustion of every pound of sulphur and that

$$\frac{64}{32} = 2 \; lb.$$

of sulphur dioxide are formed.

Sulphur will also combine according to this formula

$$S + 3O = SO_3$$

Here $\frac{1}{2}$ lb. more of oxygen is required for combustion. These products (SO_2 and SO_3) easily combine with water and form sulphurous and sulphuric acid as follows:

$$SO_2 + H_2O = H_2SO_3$$
$$SO_3 + H_2O = H_2SO_4$$

These acids strongly attack iron and hence do injury to flues and chimneys made of that material.

As pointed out previously, the heat value of sulphur is so low and the percentage of sulphur found in the average grade of coal is so small that we can easily afford to neglect it completely in our calculations.

WEIGHT OF AIR REQUIRED

So far we have been talking about and figuring for the quantity of oxygen required for the combustion of the various elements.

The only cheap source of oxygen for the purpose of combustion is the air, which is free for everyone to use. The nitrogen of the air is an incombustible gas; that is, it will not burn with oxygen no matter how much it is heated, neither will it burn with any of the combustibles of the fuels. Hence, it is entirely useless for the purpose of combustion. But, there is no economical way of separating the oxygen from the nitrogen and as they are thoroughly mixed together we must supply the nitrogen to the fire along with the oxygen.

As the ratio by weight of nitrogen to oxygen is 76.85 to 23.15, for every pound of oxygen required we must supply

$$\frac{76.85}{23.15} = 3.32 \ lb.$$

of nitrogen and hence for every pound of oxygen required we must supply

$$Oxygen + Nitrogen = Air$$
$$1 + 3.32 = 4.32 \ lb. \ of \ air$$

Col. 8, Table I, gives the pounds of air required per pound of combustible in Col. 4. These figures may be used to shorten the work when figuring the air required.

If, instead of burning just a single combustible element, such as carbon or hydrogen, we burn a fuel containing both of these elements, we figure the oxygen or the air required for the amount of each element contained in 1 lb. of the fuel just the same as though that element was the only one under consideration. The sum of the amounts of air required for each element then equals the amount of air required per pound of the fuel in question.

Thus, if we had a coal which contained, say 80 per cent. carbon; 5 per cent. available hydrogen; 2 per cent. sulphur; 1 per cent. nitrogen, and 7 per cent. ash; the air required would be estimated as follows:

Carbon contained in a pound of the coal equals 0.8 lb. From Table I, Col. 8, air required for complete combustion of 1 lb. of carbon equals 11.52 lb. Then the air required for 0.8 lb. carbon equals

$$0.8 \times 11.52 = 9.216 \ lb.$$

The available hydrogen equals 0.05 lb. Air required per pound of hydrogen (Table I) equals 34.56. Air required for 0.05 lb. hydrogen equals

$$0.05 \times 34.56 = 1.728 \ lb.$$

Adding these two quantities together, we have

Air required for carbon in coal........................ 9.216 lb.

Air required for available hydrogen.................... 1.728 lb.

Air required per pound of coal........................ 10.944 lb.

The air required for the sulphur in the coal we neglect as the amount of sulphur is small and, besides, the sulphur may already be combined with some other element and hence be incombustible anyhow. The ash and nitrogen, being incombustible, require no air.

Two more illustrations of how the weight of air required for a given weight of fuel is estimated may assist to fix the method in mind more securely. Let us assume that we are burning a fuel oil in our plant which is composed of the following: Carbon, 82 per cent.; available hydrogen, 13 per cent.; moisture, 5 per cent. How many pounds of air are theoretically required for the combustion of this oil?

In every pound of the oil there is 0.82 lb. of carbon. Then, as 1 lb. of carbon requires 11.52 lb. of air for complete combustion (see Table I, Col. 8) 0.82 lb. will require

$$0.82 \times 11.52 = 9.45 \ lb.$$

Then 13 per cent. of a pound (the amount of hydrogen contained in 1 lb. of the oil) equals 0.13 lb. Referring again to Table I, Col. 8, 1 lb. of hydrogen requires 34.56 lb. of air and hence 0.13 lb. requires

$$0.13 \times 34.56 = 4.49 \ lb.$$

Adding the two quantities of air required, we have

Air required by carbon part of 1 lb. of oil............. 9.45 lb.

Air required by hydrogen part of 1 lb. of oil........... 4.49 lb.

Total air required per pound of oil.................... 13.94 lb.

If we were burning a gas containing 70 per cent. carbon and 24 per cent. hydrogen, what would be the weight of air required per pound of gas?

Air required by the carbon in 1 lb. of gas = 0.7 × 11.52 = 8.06 lb.
Air required by hydrogen in 1 lb. of gas.................   8.29 lb.
    Total air required per pound of gas.................   16.35 lb.

This same method of calculating the amount of air required by a fuel can be expressed in the form of a formula thus:

$$W = 11.52\, C + 34.56 \left(H - \frac{O}{8}\right)$$

in which

W = Weight of air required per lb. of fuel;

C = Weight of carbon per lb. of fuel;

$\left(H - \dfrac{O}{8}\right)$ = Available hydrogen per lb. of fuel.

The available hydrogen is found by subtracting $\frac{1}{8}$ of the weight of oxygen in the fuel from the total weight of hydrogen in the fuel —just as the expression in the formula indicates.

Suppose we had a fuel with this analysis: Carbon, 78 per cent.; total hydrogen, 7 per cent.; sulphur, 1.5 per cent.; oxygen, 4 per cent.; nitrogen, 1.5 per cent., and ash, 8 per cent.   Substituting in the formula we have

$$W = 11.52 \times 0.78 + 34.56 \left(0.07 - \frac{0.04}{8}\right)$$

or

$$W = 11.52 \times 0.78 + 34.56 \times 0.065 = 11.23 \; lb.$$

of air required per pound of fuel.

For those who wish to test their understanding of what has been set forth in the foregoing chapter and who wish practice in calculations involving percentages and decimal fractions, the following problems are offered:

Given a coal with the following analysis: Carbon, 78.75 per cent.; total hydrogen, 5 per cent.; oxygen, 2 per cent.; nitrogen, 2 per cent.; sulphur, 3.75 per cent.; ash, 8.5 per cent.   Neglecting the sulphur, what is the weight of air required for complete

combustion per pound of this coal?   What would be the weight of the products of combustion?

Given a fuel oil containing: Carbon, 84.85 per cent.; available hydrogen, 11.15 per cent., and moisture, 4 per cent.   What is the weight of air required per pound of oil and what would be the weight of the products of combustion?

A feed-water heater is handling 7575 lb. of water per hour.   It raises the temperature of the water from 73 to 197.5 deg. F.   How much heat is being put into the water per hour?

These problems will be fully worked out below.

Substituting in the formula preceding the questions, the weights of carbon and hydrogen per pound of coal given in the problem, we have

$$W = 11.52 \, C + 34.56 \left(H - \frac{O}{8} \right)$$

$$W = 11.52 \times 0.7875 + 34.56 \left(0.05 - \frac{0.02}{8} \right)$$

$$W = (11.52 \times 0.7875 + (34.56 \times 0.0475)$$

$$W = 9.07 + 1.64 = 10.71 \, lb.$$

air required per pound of coal.   As the weight of the products of combustion always equals the weight of air required plus the weight of the combustibles themselves, we have

Wt. of air required + Wt. of carbon + Wt. of available hydrogen = Wt. of products of combustion

$$10.71 + 0.7875 + 0.0475 = 11.54 \, lb.$$

In finding the weight of air required for the combustion of the fuel oil, exactly the same formula is used as in the case of coal, except that the available hydrogen, represented by the term $H - \frac{O}{8}$, is given and, as a result, our work is simplified,

$$W = 11.52 \, C + 34.56 \left(H - \frac{O}{8} \right)$$

$$W = (11.52 \times 0.8485) + (34.56 \times 0.1115)$$

$$W = 9.77 + 3.85 = 13.62 \, lb.$$

of air required per pound of oil.   And, in the same way as before, the weight
of the products of combustion are

Wt. of air required $+$ Wt. of carbon $+$ Wt. of available hydrogen $=$ Wt. of
products of combustion

$$13.62 + 0.8485 + 0.1115 = 14.58 \ lb.$$

According to the definition previously given, a B.t.u., or unit of heat meas-
urement, is the amount of heat required to raise the temperature of 1 lb. of
water 1 deg. F.   In the third problem there are 7575 lb. of water per hour to
be raised in temperature.   Then,

$$197.5 - 73 = 124.5 \ deg.$$
$$7575 \times 124.5 = 943,087 \ B.t.u.$$

are being put into the water per hour.

CHAPTER II

ANALYSIS OF COAL

When you analyze a fuel you find out what it is composed of. In previous lessons we saw that the combustible or burnable makeup of all fuels consists of a few elements: Carbon, hydrogen and sulphur. Besides these combustibles a fuel contains oxygen, nitrogen and ash.

Now as the heat value of a fuel depends upon the amount of carbon, hydrogen and to a slight extent sulphur which it contains, it may be important to know what the analysis or makeup of a given fuel is so as to be able to estimate what amount of heat ought reasonably to be expected from its combustion under the boiler.

ULTIMATE ANALYSIS

There are two kinds of fuel analysis; they are called ultimate analysis and proximate analysis. The ultimate analysis tells the amount of carbon, hydrogen, oxygen, nitrogen, sulphur and ash which the dry fuel contains. In other words, ultimate analysis means complete analysis, giving the proportions of all the constituents.

To make an ultimate analysis requires expert skill, costly apparatus and a much more advanced knowledge of chemistry than we need for our study here. Ultimate analyses are seldom attempted by any but expert chemists in regular laboratories suitably fitted for the purpose. However, reports of ultimate analyses of the coal or oil of a certain district, seam or mine are often available, and, consequently, it is well to know what an ultimate analysis is and how to use it in estimating the heat value of a given fuel.

Proximate Analysis

The approximate, or as it is usually called, proximate analysis, gives the amounts or percentages of moisture, volatile matter, fixed carbon and ash contained in the fuel.

Coal is about the only fuel to which the proximate analysis is applied, although, of course, the proximate analysis of any solid fuel can be made. The proximate analysis of fuel oil is practically useless as in the average case there would be but one item, the oil being nearly all volatile matter.

The moisture is, of course, the amount of water which the coal has soaked up and this is liable to vary in a given coal from time to time, depending on the way the coal is stored, state of the weather, etc.

The volatile matter consists principally of the hydrocarbons described in the first lesson on this subject. When we say that a thing is volatile, we mean that it can be changed from the solid, the semi-solid or from the liquid state into a vapor fairly easily, and without having its nature changed; that is, without undergoing a chemical change. Quicksilver, or mercury, is a liquid-like metal which can be turned into a vapor, therefore, mercury is volatile.

In fuels, the hydrocarbons can be changed into vapors at fairly low temperatures and driven off without being burned, hence, they are called volatile. These hydrocarbons exist in a great variety of form; that is, although they all consist of nothing but hydrogen and carbon, the proportion of each varies greatly, making substances of different characteristics. Thus, marsh gas, or methane, has the chemical formula CH_4; acetylene, C_2H_2; olefiant gas, C_2H_4; ethane, C_2H_6, etc. Each combination has its own physical qualities. Some, known as "light" hydrocarbons, have the quality of vaporizing at fairly low temperatures while others, known as "heavy" hydrocarbons, do not vaporize until the temperature becomes very high. For instance, gasoline is a very light hydrocarbon, as it changes into a vapor at about 200 deg. F., while cylinder oils are composed of heavy hydrocarbons because they remain liquid at temperatures as high as 600 deg.

The fixed carbon is the pure or uncombined carbon which remains after the heating process has vaporized the hydrocarbons; it can be driven off only by actual burning and not by any process of vaporizing or distillation.

The ash is simply the unburnable solid matter which fuel contains, and consists principally of slate, dirt, etc.
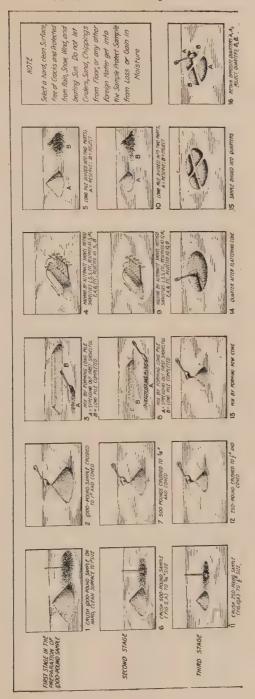
The proximate analysis is not difficult to make and it is valuable in comparing one lot of coal with another, in estimating the heat value and in checking up furnace operation.

The proximate analysis consists simply of heating an accurately weighed sample at a low temperature, for a certain length of time to dry out the moisture. The sample is then weighed again; the loss in weight divided by the original weight is taken as the percentage of moisture. The second heating (at a higher temperature this time) and the third weighing give the volatile matter. And from the third heating (at high temperature) and fourth weighing, the fixed carbon and ash are determined. Details of the method will be given later.

Taking the Sample

There are really two steps to be taken in securing a proximate analysis: First, selecting the sample; second, making the analysis itself. The reliability of the results depends upon the care taken with each step.

In selecting the sample, the object is to secure a small quantity of coal which represents the average character of a very large quantity. If the coal were of uniform character all the way through, or if the lot to be sampled could be thoroughly mixed or stirred, it would be an easy matter simply to pick up a few lumps or handfuls at any convenient point and use them as the sample to analyze. But as such is not the case it is necessary to select many small quantities from all parts of the lot, of such size that when all are put together the pile will be small enough to thoroughly turn and mix after which a suitable sample can be taken therefrom. No exact rules can be offered to suit all cases, and

NOTE

Select a hard, clean Surface, free of Cracks and Protected from Rain, Snow, Wind, and beating Sun. Do not let Cinders, Sand, Chippings from Floors or any other foreign Matter get into the Sample. Protect Sample from Loss or Gain in Moisture

FIRST STAGE IN THE PREPARATION OF 1,000-POUND SAMPLE

1 CRUSH 1,000-POUND SAMPLE ON HARD, CLEAN SURFACE TO 1" SIZE

2 1,000-POUND SAMPLE CRUSHED TO 1" AND CONED

3 MIX BY FORMING LONG PILE
A = SPREADING OUT FIRST SHOVELFUL
B = LONG PILE COMPLETED

4 MIXING BY ALTERNATE SHORT METHOD
SHOVELFULS 1,3,5, ETC. BUILT UP AS S, A;
2,4,6, ETC. MIXTED AS S, B

5 LONG PILE DIVIDED INTO TWO PARTS:
A = RESERVE; B = REJECT

SECOND STAGE

6 CRUSH 500-POUND SAMPLE
(FIG 5, A) TO 3/4" SIZE

7 500 POUNDS CRUSHED TO 3/4" AND CONED

8 MIX BY FORMING LONG PILE
A = SPREADING OUT FIRST SHOVELFUL
B = LONG PILE COMPLETED

9 MIXING BY ALTERNATE SHORT METHOD
SHOVELFULS 1,3,5, ETC. BUILT UP AS A, A;
2,4,6, ETC. MIXTED AS B, B

10 LONG PILE DIVIDED INTO TWO PARTS;
A = RESERVE; B = REJECT

THIRD STAGE

11 CRUSH 250-POUND SAMPLE
(FIG 10,A) TO 1/2 SIZE

12 250-POUND CRUSHED TO 1/2" AND CONED

13 MIX BY FORMING NEW CONE

14 QUARTER AFTER FLATTENING CONE

15 SAMPLE DIVIDED INTO QUARTERS

16 RETAIN OPPOSITE QUARTERS A, A;
REJECT QUARTERS B, B

FIG. 7.—Bureau of mines directions for sampling coal.

the method of sampling must be adapted to the local conditions. If the quantity of coal to be sampled is large, care must be taken to avoid making the sample pile too large to work thoroughly, yet, at the same time, the pile must be composed of as many small samples as possible in order that it will closely represent the real character of the coal.

One commonly used method where coal is received in carload lots is to make a corer which can be driven down through the coal in several places in the car. This method gives samples of the coal from top to bottom at the various points, and when thoroughly mixed these samples may be taken as a fair average for the whole car. The corer may be made of heavy 2- or $2\frac{1}{2}$-in. iron pipe, 5 or 6 ft. long, sharpened at one end and with the other end capped or reinforced so that it can be driven with a sledge. Enough samples should be taken with the corer to make a large sample of 50 to 100 lb. Any lumps in this large sample should then be crushed so that there are no pieces larger than $\frac{1}{2}$ in. diameter, after which the sample should be thoroughly mixed and "quartered down" until about 5 lb. remain.

This "quartering down" is done by spreading the sample out thin in the shape of a circle; dividing this circle into quarters, and throwing away the first and third quarters, as shown in Fig. 3. Thus, the quantity is reduced one-half. The
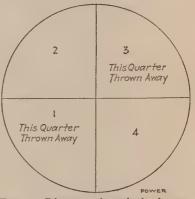
FIG. 3.—Diagram of method of quartering sample.

two remaining quarters are then mixed thoroughly, spread out and again quartered. This process is continued until the remainder of the sample is of the desired size.

If the sample is not to be analyzed right away it should be put

into a glass jar or a tin fitted with a tight cover and stored in a reasonably cool place until used.

Apparatus Required for Proximate Analysis

The following pieces of apparatus or their equivalent are required for making a proximate analysis:

1 chemist's balance (sensitive to 1 milligram)............	$12.00
1 set of weights (50 grams to 1 milligram)...............	2.25
1 porcelain crucible with cover (15 c.c. capacity).........	0.15
1 iron ring stand or iron tripod........................	0.25
1 Bunsen burner or gasoline blow torch, 25c. or.........	2.75
1 desiccator (sulphuric acid) (4 in. in diameter)..........	1.25
1 lb. sulphuric acid (chemically pure)....................	0.30
1 drying oven..	1.10
1 100-mesh sieve (small size)...........................	1.40
1 mortar and pestle (porcelain).........................	0.35
2 porcelain insulated wire triangles (2-in.)..............	0.15
1 pair crucible tongs...................................	0.35
1 coffee mill (cast iron)...............................	1.15
	————
	$23.45

Thus, you see, for a total cost of less than the price of a good steam-engine indicator any man can own the means of examining the coal used in his plant. And, although the indicator is a splendid instrument for effecting economy, it is even more important to examine into the character of the coal you purchase. If the ash or moisture content in a certain lot of coal is larger than normal, you should know it and take steps to avoid being "stuck" in a similar way again. If the character of the combustible part of the coal undergoes a marked change you should know it in order that the firing methods may, if necessary, be changed to suit.

It certainly is to the best interests (in every sense of the word) of every engineer operating a coal-burning plant, to analyze, if not a sample from every shipment of coal received, at least frequently enough to know with fair certainty whether the character
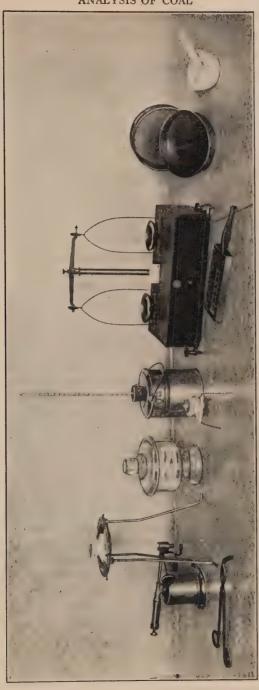
Fig. 4.—Apparatus required for proximate analysis.

of the coal changes, and to keep a record of all analyses together with the price of the coal from year to year for the purpose of future reference.

Now, the cost shown by my list may be reduced somewhat by substituting home-made apparatus and this point will be taken up as we discuss each individual piece.

The Balance

The most important piece of apparatus is the balance and the price given in the list is that of about the cheapest that can be used. More sensitive balances, capable of giving close results, would cost $25, $50, $75 or $100. But for the average power-plant requirements the $12 balance is satisfactory when used carefully. An actual picture of such a balance is seen in the assembly view, Fig. 4, and a sketch is given in Fig. 5.

The box rests on three legs, a stationary one at the rear and the two adjustable ones A at the front of the sides, by means of which the balance is leveled. The leveling in the present case must be done by placing a small spirit level on the top of the box, first extending left and right, then front and back, and adjusting the thumb-screws to suit. Some balances are fitted with a small plumb-bob for leveling, in which case the spirit level is unnecessary.

The balance beam, fitted with a small knife-edge shaft of hard steel at its middle, rests in the saddle B, at the top of the upright, which has V-shaped hard-steel bearings. A hard-steel knife-edge shaft at each end of the beam carries a stirrup with hard-steel V-shaped bearings from which the scales are hung. The scale pans C are removable. The saddle B is raised and lowered by means of the thumb-screw C; in the lowered position the scales rest on the box, as shown; in the raised, they clear the box by about $\frac{3}{8}$ in. and the beam is thus free to swing and indicate whether the contents of the pans are equal in weight or not. The object of this arrangement is to make it more easy to load and unload the pans. The balance is so sensitive that if you attempted to lift one pan off or take out or put in a weight much greater than I

gram, the other pan, unless first supported or steadied, would bang down on the box and perhaps upset whatever it contained or even dislocate its stirrup on the beam above. Thus, before greatly disturbing the equilibrium it is convenient to lower the pans so that they rest on the box. Of course, when weighing, after an approximate balance has been established, the addition to or removal from the weight pan of a weight of 200 milligrams or less does not make the balance swing violently and the pans need not be lowered.

Before weighing, the balance should be tested by putting the empty pans in the scales, raising the beam and noticing whether the pointer D either remains on the center line of the scale E or swings an equal number of divisions to each side of the center line. If slight adjustment is necessary this can be made by turning the adjusting screw F one way or the other until the balance is correct. Best results are accomplished when the balance is placed where it is free from even the slightest air currents and uneven variations in temperature. The more expensive balances are housed in glass cases which have fronts that slide up and down, the cases being closed when the final balancing is being tried. The ingenious man who wishes to get the best results with his $12 balance may build a glass case for it, constructing the case, of course, so that the thumb-screw C, for raising and lowering the scales, projects through the front and can be manipulated when the front is closed.

The weights are furnished in a special box which has compartments for each size and they should always be kept in the box. As soon as a weight is removed from the balance it should be placed directly in its compartment and not laid upon the table or anything else when it is in danger of becoming lost, dirty or damaged. A pair of forceps for handling the weights is furnished with every set and should always be used in preference to the bare fingers as moisture from the latter is liable to cause tarnishing or the accumulation of dirt, or other foreign matter.

The weights are based on the French or metric standards; the units used being grams and milligrams. The reason for using

the French units instead of the English pounds, ounces, etc., is that as the French units are based on the decimal system they make calculation more simple. A gram equals about 0.035 of an ounce. One milligram equals $\frac{1}{1000}$ of a gram, and, hence to reduce grams to milligrams or *vice versa* it is simply a matter of adding the right number of ciphers or locating the decimal point. To illustrate, 526 milligrams equal 0.526 gram; 62 grams equal 62,000 milligrams; 13.27 grams equal 13,270 milligrams, etc.

One set of weights consists of one 50-gram, two 20-gram, one 10-gram, one 5-gram, two 2-gram, one 1-gram, one 500-milligram, two 200-milligram, one 100-milligram, one 50-milligram, two 20-milligram, one 10-milligram, one 5-milligram, two 2-milligram and one 1-milligram weights, so that their range is from 1 milligram (0.001 of a gram) up to 111.11 grams advancing by milligrams.

CRUCIBLE
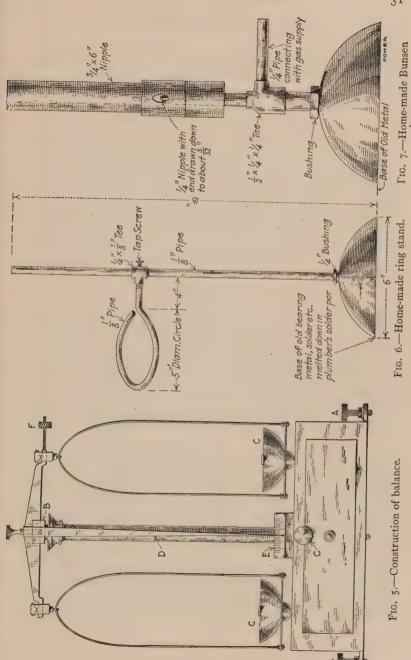
The crucible is the little vessel in which the sample of coal is heated. One made of porcelain will answer all our purposes. In ordering, specify the 15-c.c. size with lid. Its cost is so small that while a fair substitute could be devised it is not worth while doing so as the extra care required in handling would more than offset the saving effected.

The ringstand, shown in Fig. 6, can easily be made from ⅛-in. iron pipe and fittings, and, being adjustable, it is more convenient to use than the tripod shown in Fig. 4.

If a good supply of gas is available (as in almost any city) a bunsen burner is the most convenient form of heater to use. If not, a gasoline blow torch, such as shown in Fig. 4, will be needed; or an ordinary plumber's or electrician's torch will do nicely. The latter, however, usually gives a horizontal flame and will have to be tilted a little in order to make the flame strike the oven or crucible to best effect.

A home-made Bunsen burner as per Fig. 7 will give just as satisfactory results as a purchased burner. To regulate the air

FIG. 7.—Home-made Bunsen burner.

FIG. 6.—Home-made ring stand.

FIG. 5.—Construction of balance.

supply a loose sleeve is placed above the union on the $\frac{3}{4}$-in. nipple and is provided with four holes to match the holes in the nipple.

DESICCATOR

When the moisture has all been driven off from the sample of coal by the first heating and the sample is dry and still hot it would rapidly absorb moisture from the air if left exposed to it in that condition. And the same thing would happen after each subsequent heating if the sample were left exposed to the ordinary air.

Hence, the sample is transferred direct from the oven or from the tripod to the desiccator or drier to cool off before being weighed. The commonest form of desiccator is that shown in Fig. 4. It consists simply of a glass jar and lid; the joint between jar and lid being ground to an air-tight fit. The lower part or well of the desiccator is about quarter or half filled with pure sulphuric acid. The upper part contains a glass or porcelain tray upon which to set the crucible containing the sample of coal.

The principle of the desiccator is this: Sulphuric acid has a strong affinity for water or moisture. Hence, with an air-tight lid, what little moisture there is in the air entrapped in the desiccator is soon absorbed by the acid and the hot sample of coal does not get a chance to absorb any moisture and thus cause an error in the analysis.

One pound of chemically pure sulphuric acid (enough for use in the desiccator for a long time) can be purchased for 30c.; this includes the glass-stoppered bottle to contain it. How long the acid in the desiccator will remain effective depends on the manner in which it is used. If means are available for accurately weighing the acid or the desiccator before and after the acid has been put in, the acid may be renewed when the gain in weight is equal to 25 per cent. of the original weight of the acid. To illustrate, suppose $\frac{1}{4}$ lb. (or about 113 grams) of the dry acid were put into the desiccator and after six months or a year, the weight was found to be 5 oz. (a gain of 25 per cent.) it would then be

advisable to refill the desiccator with fresh acid. If it is not convenient to check up the condition of the acid by weighing, it is safest to renew it about once a year.

Great caution must be used in handling sulphuric acid as it will attack or "eat away" the clothing, also iron, copper and many other metals. And, if it comes in contact with flesh it may cause a bad burn. Keep the bottle where it is not in danger of being broken and be sure that none of the acid is allowed to spill out of the desiccator. Also, never allow any water to come in contact with the acid as much heat is generated thereby and the acid might spatter on the face and hands. Always keep the lid on the desiccator to prevent the acid from absorbing moisture from the air and thus becoming weakened too soon.

DRYING OVEN

The drying oven is used for the first heating of the sample to determine the moisture content.

If you were to purchase a standard oven it would cost at least $5. The oven shown in Fig. 4 can be manufactured for $1.10 or even less. Secure a 1-qt. tin pail (about 4 in. in diameter by about $4\frac{1}{4}$ in. high) cost 10c. Punch a hole, about $1\frac{1}{4}$ in. in diameter, in the center of the lid. Next, secure a good sound cork to fit the hole and bore a hole in the cork so that the thermometer will fit in it snugly, as shown.

See that the lid of the pail fits loosely so that it can be removed without the necessity of holding the pail, as the latter will be hot and awkward to handle most of the time and the sample might be spilled if force is used. If necessary, cut off or bend in the flange on the lid. Punch a hole about 1 in. in diameter in the bottom of the pail and one or two small ones in the lid to provide for a small circulation of air.

Purchase a chemical thermometer having a range from zero to 200 deg. C., cost $1. Insert this in the cork, as shown in Fig. 4, so that the bulb projects into the pail about $1\frac{3}{4}$ in.

Bend down the ends of a porcelain-insulated wire triangle so as

to form a little stand for the crucible, as shown in Fig. 8.   Put
this stand in the pail and place the pail on the ringstand or tripod
over the burner and our home-made oven is ready for "business."

The next item on our list, the 100-mesh sieve, is desirable but
not absolutely essential.   It is used for sifting the sample before
the analysis.   If economy in first cost is imperative, the sample
may be prepared without sifting, but extreme care should be used
to crush the sample uniformly and as fine as possible.
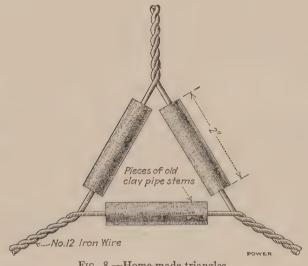
FIG. 8.—Home-made triangles.

The mortar and pestle, for crushing the sample, may also be
dispensed with if desired; but the price is so small and they are so
convenient that this is not recommended.   If the sample is
crushed with a hammer in an iron pot, on a sheet of iron, slab of
stone or other hard surface, care must be taken that particles of
incombustible foreign matter do not get mixed with the coal, thus
causing an error in the analysis.

The next item on the list, the porcelain-insulated wire triangles,
are used, one for supporting the crucible on the tripod or ringstand

over the flame, the other, bent as just described, for supporting the crucible in the drying oven. Satisfactory home-made triangles may be made as shown in Fig. 8.

The crucible tongs, shown in Fig. 4, are used for handling the crucible and lid throughout the analysis. A pair of home-made tongs could be devised, but it is doubtful if the effort is worth while as they probably would not be as "handy" or as smooth working as a purchased pair.

The last item on the list, the coffee mill, is employed to coarsely grind the sample before it receives the final mixing and crushing. If an old coffee mill is available, so much the better, as it will answer just as well as a new one and the cost of the new one will be saved. It should be strong enough, however, to stand the service. One made of cast iron would be suitable.

MAKING THE ANALYSIS

You have now been introduced to all the apparatus needed in making a proximate analysis and all that remains to be acquired is a little practice in handling the equipment and running the actual analysis. Run five or six analyses just for the practice.

From the outset, remember that the more careful and painstaking you are with the work, the more accurate and reliable will be the results. The sample dealt with, 1 gram, and the differences to be determined in the weight of that sample after each step, are so small that it requires but a slight inaccuracy to throw out the entire work.

Get into the habit of following exactly the same process with each analysis. Do not use one method one day and then vary it, even slightly, the next. Decide by experiment in the beginning the best method for you to follow and stick as closely to that method as possible with all your analyses. The object of this advice is to insure uniformity in results. If you use one method one day and a slightly different method the next, the results are not likely to be uniform. And what you want is a fair comparison, one day with another.

A good method to follow is this: Assume that a 5-lb. sample of the coal to be tested has been collected as described. Rule off a form on which to record the analysis. The one shown, already filled out, in Fig. 9 is convenient but may need slight modifications to suit special needs. If you expect to analyze coal regularly, it will pay to have the form printed or mimeographed.

First, see that the crucible is thoroughly clean and dry. Then weigh it, together with its cover, as accurately as possible, remem-

PROXIMATE ANALYSIS OF COAL

Plant. *Progress Mfg. Co.* ....
Car Nos. *C. & S. 74331,B&R 14865.* .....Total Tons in Shipment. *80* .....
Date Received *Jan. 7, 13.* Date Sample Taken *Jan. 7, 13.* Date Analyzed *Jan. 10, 13*
Analyzed by. *Earnest Wheatt* ......

	Grams		Analysis of Coal as Received	Analysis of Dry Coal
Wt. of crucible and lid plus sample.........	*21.522*			
Wt. less moisture.......	*21.445*	Per cent. moisture	*7.7*	
Wt. less volatile matter..	*21.167*	Per cent. vol. matter	*27.8*	*30.12*
Wt. less fixed carbon....	*20.637*	Per cent. fixed carbon	*53.0*	*57.42*
Wt. of empty crucible with lid..............	*20.522*	Per cent. ash.......	*11.5*	*12.46*

Heat value of dry coal
(by calorimeter) ....B.t.u. per lb.   Cost of Coal, $.... *2.90* .... per ton
Heat value of combust-
ible (estimated) *13,375* .B.t.u. per lb.   No. B.t.u. purchased
                                          for 1 cent......... *85,676* ....
Heat value of dry coal
(estimated). *12,457,* .B.t.u. per lb.
Heat value of coal as received
(estimated). *12,473* ...B.t.u. per lb.

FIG. 9.—Proximate analysis report form.

bering to test the balance first. Weigh the crucible and cover before every analysis, to be sure that the weight is accurate, for if a slight chip should break off from either, the results would be wrong unless the new weight of the crucible were used. Enter the weight in the proper space on the report sheet. Then, fill out the first space by adding 1 gram to the weight of crucible and lid.

When weighing it is not necessary to wait for the balance to come to rest each time; simply notice whether the pointer swings uniformly a given number of divisions each side of the center line on the scale. But be sure that the swing is exactly uniform. Leave the crucible in the scale pan ready to receive the sample.

Spread out the 5-lb. sample on a clean surface (such as a piece of newspaper) mix thoroughly and quarter down to about 1 lb. Put this quantity through the coffee mill once or twice, grinding as fine as possible with the mill. Again mix and spread out thin on a clean surface. Then, with a knife blade, select small quantities from a half dozen places in the mass and put them in the mortar, thus obtaining about 1 oz. Crush thoroughly with the pestle. Sift this finely crushed sample through the 100-mesh sieve into the tray that comes with the latter. If any of the sample will not pass through, put it back into the mortar and crush until practically all passes through.

If you are working without a sieve be sure that the sample is crushed fine enough. It should look like a very fine dust—so fine and uniform that no individual particles are distinguishable.

Now, add 1 gram to the weights in the balance and put enough of the powdered sample into the crucible to again restore equilibrium.

Put the crucible (without cover) into the oven and heat to 110 deg. C. for 1 hour. Keep heat as uniform as possible. Now, quickly transfer the crucible to the desiccator and allow it to cool off. This will take about 10 minutes. When cool, weigh crucible (with lid on) and enter weight in the second space on the report sheet. Subtract this weight from the one above, move the decimal point two places to the right and enter result as percentage of moisture in the proper space.

Next, place the crucible, with lid on and in an upright position, on the triangle and ringstand over the burner, as shown at the left in Fig. 4. Turn the flame up strong and heat the crucible for full 7 minutes. The flame should be long enough and placed close enough to the crucible to completely envelop it and shoot above for a distance of an inch or more.

At the end of the 7 minutes remove the flame and transfer the crucible and lid to the desiccator to cool.   Inspect the sides of the crucible to make sure that the porcelain insulators on the triangles have not softened under the heat and left small particles sticking to the former.   If this occurs the analysis will have to be done over, as the weighing would be inaccurate.   If this occurs frequently, a "Nichrome" wire triangle will have to be used instead of the porcelain insulated one.   The cost of one of this kind is about 35c., but it is durable and will not stick.

In heating to drive off the volatile matter a black smudge of carbon will probably be made on the outside of the crucible. Most people burn this off before transferring to the desiccator by playing the flame on the sides.   I am not going to advise you to do this because, unless carefully done, it leads to the breakage of crucible or lid, thus spoiling an analysis.   Besides, the error caused is so *very* slight that it is hardly worth the trouble taken to eliminate it, and, if the same practice is followed each time, the importance of the error is still more reduced.   However, before another analysis is made in the crucible both it and the lid should be cleaned by carefully burning off this carbon deposit.

When the crucible is cool, weigh and enter the weight as before. The loss in weight this time represents the percentage of volatile matter contained in the coal.

Next, place the crucible, without cover, on the stand again, only this time tilt it as far on its side as you can without danger of any of the contents being spilled or blown out.   Turn the flame on strong, as before, and heat thus for at least 2 hours.   See that the flame concentrates under that part where the sample lies.

At the end of the heating, cool in the desiccator and weigh again with the lid.   The loss in weight this time represents the percentage of fixed carbon.   And, the difference between this last weight and the weight of the empty crucible with lid represents the percentage of ash in the coal.

The analysis is now finished and all that remains is to stow the apparatus safely away until next needed and to calculate the analysis of the dry coal.

The analysis which we have just completed is that of the coal "as received." Strictly speaking, it is not the true analysis of the coal as received because some of the moisture dried out while the sample was being prepared for testing. But, as long as about the same length of time is taken up in preparing the sample in each case and as long as the process of treatment is the same, the error remains about the same and, so, we may call it the "as received" analysis and do no particular harm.

With some grades of coal which have a great capacity for absorbing moisture it is necessary to air dry the sample before it can be passed through the sieve. In such cases if extreme accuracy is important, a preliminary air-drying test must be made and the moisture thus eliminated must be included in the calculations. But as this complicates matters somewhat, I do not recommend that it be attempted in ordinary work. If the coal will not sift through the sieve readily when first crushed, it may be allowed to stand exposed to the air for one-half to one hour. A better method to employ, because it insures more uniform analyses, is to coarse grind a sample of a pound or two in the coffee mill, spread it out in a thin layer and leave it exposed to the air at 70 to 80 deg. F. for 24 hours. If this method is adopted regularly, the term "air dried" should be substituted for "as received" throughout the report form in Fig. 9.

To figure the analysis of the dry coal from the analysis of the "as received" sample, simply divide the percentage of volatile matter, fixed carbon and ash (each in turn) by the sum of all three. Thus, taking the analysis given in Fig. 9, the sum of the percentages of volatile matter, fixed carbon, and ash is,

$$27.8 + 53 + 11.5 = 92.3$$

This sum divided into the percentage of volatile matter gives

$$\frac{27.8}{92.3} = 30.12$$

as the percentage of volatile matter in the dry coal.

The reason is simple. Let us assume 100 lb. of coal of the analysis given. As the analysis shows 7.7 per cent. moisture,

7.7 lb. is water, leaving only 92.3 lb. when the coal is thoroughly dry. The analysis also shows 27.8 lb. volatile matter in every 100 lb. of the coal as received. Then, what fraction of the dry coal is the volatile matter?

$$\frac{27.8}{92.3} = 0.3012 \text{ } or \text{ } 30.12 \text{ } per \text{ } cent.$$

In a like manner, the percentages of the other two constituents, fixed carbon and ash, are figured.

Estimating Heat Value of Fuel

The heat value of a fuel is estimated either by actually burning a small sample and measuring the heat given off or by calculation based on either the ultimate or the proximate analysis. The first is the more accurate method, but as the cost of the required apparatus is rather high, and as it is not important for everyday work to know the exact heat value of every lot of coal received, we will pay most attention to the second method and pass over the first after giving a brief description in order that you may be familiar with it in a general way.

Coal Calorimeter

The sample burned is as carefully selected and prepared as the sample used for the proximate analysis, and its weight is usually the same, 1 gram. It is burned in a device called a calorimeter— a name derived from the words caloric, meaning heat, and meter, meaning measurer.

Fig. 10 illustrates a simple form of the commonest type of coal calorimeter. The bomb or crucible C of iron or steel and lined with some material which is not affected by the products of combustion, contains the sample of coal to be tested, and is suspended in the water chamber B as shown. This water chamber is surrounded by the casing A to reduce error due to radiation. The stem F is hollow and closed off at the upper end

by a valve. The wooden lid H is tight fitting. To load the bomb C it is taken out and unscrewed from the cap G. The sample of coal, thoroughly mixed with the proper amount of some chemical which gives up oxygen when heated (usually sodium peroxide) is put into the bomb and the latter is again screwed into place.
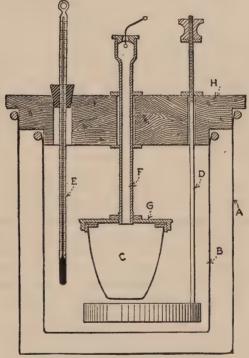
Fig. 10.—Simple form of coal calorimeter.

A quantity of water, which has been exactly measured, is then put into B, and when the lid H is again fixed in place, the calorimeter is ready for the test. The water is stirred for a few minutes with the paddle D until the thermometer E shows that the temperature has ceased changing. Then the valve at the top of the

stem F is opened, a small piece of red-hot nickel wire is dropped in
and the valve quickly closed again.

Rapid and complete combustion takes place due to the libera-
tion of the oxygen from the chemical mixed with the coal.   The
heat-laden products of combustion are all trapped in the bomb
and hence must give up their heat to the surrounding water, which
is again stirred for several minutes to hasten the transfer and to
maintain uniformity.   The rise in the temperature of the water
is carefully noted, the thermometer being graduated to read in
small fractions of a degree.

Knowing the weight of the water and the rise in temperature,
the number of heat units generated by the sample can easily be
calculated by multiplying these two factors together, and the heat
value of a pound of fuel can then be found by multiplying by a
constant, which takes into account the ratio of weights and other
factors involved.

Heat Value by Calculation

As has been pointed out, the combustion of a given element
always results in the generation of a fixed amount of heat.   Thus,
when a pound of pure carbon burns completely (forming CO_2)
14,600 B.t.u. is produced.   When 2 lb. is burned, 29,200 B.t.u. is
generated, and so on.   Consequently, the heat value of carbon is
said to be 14,600 B.t.u.—which means 14,600 B.t.u. per lb., as the
pound is the unit of weight almost universally used in this
country.

When a pound of pure carbon burns incompletely (forming
CO), only 4450 B.t.u. is produced.   But if, in turn, the resulting
$2\frac{1}{3}$ lb. of CO., which is a combustible gas, is burned, 10,150
additional B.t.u. is liberated, making the total heat produced
equal to 14,600 B.t.u., just the same as though the pound of
carbon had burned completely (to CO_2) in the first place.   Hence,
the heat value of CO is

$$\frac{10,150}{2.333} = 4350 \; B.t.u. \; per \; lb.$$

The heat value of pure hydrogen is 62,000 B.t.u. per lb.

These heat values for carbon and hydrogen were established by experiment and hence probably are not absolutely exact. In fact, some authorities give values for carbon as low as 14,220, and as high as 14,647, and for hydrogen as low as 61,816 and as high as 62,032, but as the ones given (14,600 and 62,000) are the most widely accepted and used, it is best to accept them for use in our work.

The heat value of sulphur, the only other heat-producing element in the common fuels, is 4050 B.t.u. per lb. While this fact is interesting, it is not important in practical work, because in addition to the heat value of the sulphur itself being low, the percentage of sulphur in the average fuel is also low; besides, the sulphur may not be pure and hence may have no heat value whatever. Thus the amount of heat due to the sulphur is very small compared with that given up by the two main elements, carbon and hydrogen.

To estimate the heat value of a pound of fuel containing both carbon and hydrogen, simply multiply the percentage of total carbon in the fuel (expressed as a decimal) by 14,600, the percentage of available hydrogen (also expressed as a decimal) by 62,000 and add the results together.

To illustrate, assume we wish to estimate the heat value of a coal with this analysis: Carbon, 68.12 per cent.; hydrogen, 4.98 per cent.; oxygen, 7.42 per cent.; nitrogen, 1.98 per cent.; sulphur, 4.54 per cent.; ash, 12.96 per cent.

The heat due to the carbon is

$$0.6812 \times 14,600 = 9945.5 \; B.t.u.$$

The available hydrogen equals

$$0.0498 - \frac{0.0742}{8} = 0.0405$$

and this, multiplied by the heat value of hydrogen,

$$0.0405 \times 62,000 = 2511 \; B.t.u.,$$

the heat due to the hydrogen in the coal.   The sum of these two
quantities is

$$9945.5 + 2511 = 12,456.5 \ B.t.u.$$

the heat value of the coal.

Heat Value by Formula

The foregoing method can be expressed in a formula as follows:

$$C \times 14,600 + \left(H - \frac{O}{8}\right) \ 62,000 = B.t.u. \ per \ lb.$$

where

C = Decimal part by weight of carbon in the fuel;
H = Decimal part by weight of hydrogen in the fuel;
O = Decimal part by weight of oxygen in the fuel.

To apply this formula to another example, assume a coal with
this analysis: Carbon, 65.23 per cent.; hydrogen, 4.95 per cent.;
oxygen, 14.85 per cent.; nitrogen, 1.66 per cent.; sulphur, 2.10 per
cent.; ash, 11.21 per cent.   Substituting in the formula, we have

$$0.6523 \times 14,600 + \left(0.0495 - \frac{0.1485}{8}\right) \ 62,000$$
$$= 11,439 \ B.t.u.$$

The foregoing method of formula may be used for any other kind
of fuel or for oil, wood, gas, etc.   In dealing with gas, however,
care must be used that volumes and weights are not confused to
produce error.   A common method of stating the heat value of
a fuel gas is in *B.t.u.* per cubic foot or per 1000 cu. ft.   In such
cases the temperature and pressure of the gas must also be speci-
fied because these influence the volume greatly.   The temperatures
most frequently taken are 32 and 60 deg. F., and the pressure,
14.7 lb., absolute.

Heat Value from Proximate Analysis

The proximate analysis of coal does not give the percentage of
hydrogen, the percentage of oxygen nor the percentage of total
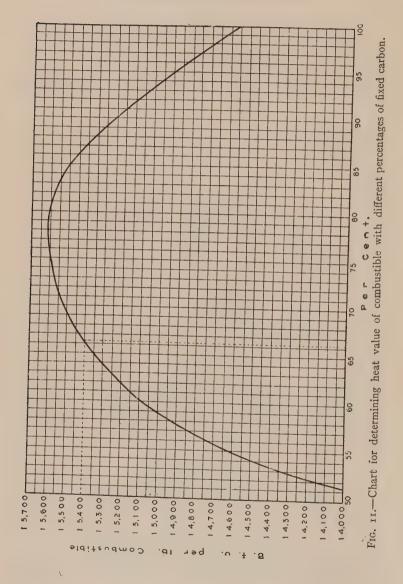
carbon. It does give the percentage of fixed carbon, but in addition to this the fuel contains some carbon which forms part of the volatile matter and the amount or percentage of this volatile carbon cannot be found except by the ultimate analysis. Hence, the formula just given is of use only in those few cases where the ultimate analysis is available, so that other methods will mostly have to be used in our work.

Some relation exists between the percentage of fixed carbon in the combustible matter of coal and the heat value of the combustible matter. To illustrate, if the combustible matter of a given coal consists of, say, 60 per cent. fixed carbon and the other 40 per cent. volatile matter, it is probable that the heat value of a pound of such combustible matter will be found to be about 15,080 B.t.u. This does not apply closely to all coals, but it applies closely enough to most coals to be useful in the absence of a better or more accurate method of estimation that can be used with the proximate analysis.

Fig. 11 is based on this fact. This chart was constructed from over 300 analyses, representing coal found in 27 states and territories, made by the United States Government and published in numerous bulletins. It is almost exactly correct for a limited number of cases, reasonably near correct (probably within 3 per cent.) for a large number of cases and quite far from correct in a few cases. The curve is most uniformly accurate for coals which have combustible matter containing from 64 to 90 per cent. fixed carbon. Where the fixed carbon runs less than 64 per cent. the curve may, in a few cases, err as much as 7 per cent.

Application of Chart

To estimate the heat value of a coal with a given proximate analysis, add together the percentage of fixed carbon and the percentage of volatile matter in the coal; divide this sum into the percentage of fixed carbon and multiply by 100. This gives the percentage of fixed carbon in the combustible matter. Locate this percentage at the foot of the chart, extend your pencil straight

FIG. 11.—Chart for determining heat value of combustible with different percentages of fixed carbon.

up until you strike the curve, then extend it to the nearest (left or right) margin in a straight horizontal line and read off the B.t.u. per pound of combustible. Multiply the B.t.u. thus found by the sum of the percentage of fixed carbon and volatile matter in the coal as shown by the proximate analysis, and the answer, divided by 100, gives the B.t.u. per pound of coal.

To illustrate with an actual example, assume a coal with this proximate analysis: Moisture, 5.12 per cent.; volatile matter, 27.25 per cent.; fixed carbon, 53.38 per cent.; ash, 14.25 per cent. Adding together the percentage of fixed carbon and the percentage of volatile matter,

$$53.38 + 27.25 = 80.63.$$

Dividing this into the fixed carbon, we have

$$53.38 \div 80.63 = 0.662,$$

which, multiplied by 100, gives 66.2 per cent. fixed carbon in the combustible. Referring to the base line of the chart, find the 66 per cent. line and judge a point 0.2, or $\frac{1}{5}$, of the distance to the next line beyond. Trace an imaginary vertical line (this line is shown dotted on the chart) up from this point to the curve and then horizontally to the left margin. It strikes exactly the 15,400-B.t.u. line. Then, 15,400 B.t.u. may be taken as the heat value of a pound of combustible matter such as found in the coal given in the example.

Now, if the coal was all combustible and had no moisture nor ash, the heat value per pound of coal would be identical with the heat value per pound of combustible. But only 80.63 per cent. of the coal is combustible, and hence the heat value of a pound of coal is equal to only 80.63 per cent. of the heat value of a pound of combustible. Thus, the heat value of the coal is

$$15,400 \times 80.63 \div 100 = 12,417 \ B.t.u.$$

Exercise Problems

What is the heat value of a coal with the following ultimate analysis: Carbon, 63.65 per cent.; hydrogen, 5.26 per cent.;

oxygen, 10.12 per cent.; nitrogen, 1.59 per cent.; sulphur, 5.03 per cent.; ash, 14.35 per cent.?

Estimate the heat value of a coal which has this proximate analysis: Moisture, 1.36 per cent.; volatile matter, 35.51 per cent.; fixed carbon, 50.06 per cent.; ash, 13.07 per cent.

Following are the solutions of the problems in the above paragraph. Applying the formula given in the same chapter as the problems we have

$$C \times 14,600 + \left(H - \frac{O}{8}\right) 62,000 = 0.6365 \times 14,600$$

$$+ \left(0.0526 - \frac{0.1012}{8}\right) 62,000 = 11,773 \ B.t.u. \ per \ lb.$$

In the second problem the sum of the percentages of volatile matter and fixed carbon is

$$35.51 + 50.06 = 85.57$$

and dividing this into the percentage of fixed carbon and multiplying the quotient by 100 gives

$$\frac{50.06}{85.57} \times 100 = 58.5$$

the percentage of fixed carbon in the combustible. After locating the 58.5 point at the bottom of Fig. 11, in the last lesson, tracing an imaginary line straight up to the curve and then horizontally across to the left margin, we find that the heat value per pound of combustible matter is 14,975 B.t.u. Then, as but 85.57 per cent. of the coal in the problem is combustible matter, the heat value per pound of coal is

$$14,975 \times 85.57 \div 100 = 12,814 \ B.t.u.$$

CHAPTER III

FLUE GAS ANALYSIS

Let us assume that we have succeeded in discovering the best coal, all things considered, for our plant. By making proximate analyses and estimating heat values we have found one grade of coal which has minimum moisture and ash; consequently, it gives maximum heat-generating material per dollar invested. Upon actual trial in the boiler room it is found to work satisfactorily with the existing equipment. It does not clinker badly and, hence, the firemen can handle it easily and efficiently and maintain the stem pressure uniform without undue trouble.

Our next problem is: How best to burn this coal so as to get most of the heat it contains into the boiler and generate the greatest quantity of steam possible per pound of coal fired. And right here is where our knowledge of the underlying principle of combustion comes into use.

Excess Air Necessary

In preceding chapters it was shown that each pound of coal of a certain composition requires a certain fixed weight of air for complete combustion and the method of figuring this weight was given. But, this theoretically required amount of air will not suffice in the boiler plant because if only the required amount is supplied, the distribution must be perfect so that each particle of oxygen in the air may come in contact with a particle of carbon or hydrogen. If this does not take place, some of the oxygen will escape without combining with its allotted share of the combustible matter, with the result that either of the two following things may happen: Some of the hydrogen may escape unburned, or some of the carbon may be only partly burned and form CO instead of CO_2.

In the boiler plant this perfect distribution of the oxygen is impossible. Consequently, an excess quantity of air must be

supplied to the fuel in the furnace in order that complete com-
bustion of every particle of the burnable matter may be effected
and no loss suffered from combustible gases escaping up the
chimney.

IMPORTANCE OF KNOWING REQUIRED EXCESS

Now, too much excess air is equally or even more detrimental
to good economy than too little.   Assume a given coal requires
10 lb. of air per lb. of coal for complete combustion and that the
gases formed weigh 10.75 lb.   The heat value of a pound of this
coal is, say, 10,000 B.t.u.   Immediately after combustion all
this heat is contained in the 10.75 lb. of gases and due to this fact
their temperature is very high.   We are not ready just yet to
estimate how high, so let us assume the temperature to be 3500
deg. F.   As these intensely hot gases come in contact with the
heating surface of the boiler and give up their heat to the water
within, their temperature falls until it reaches, say, 500 deg.
as the gases leave the boiler.   The gases are still much hotter than
was the air and coal which went to make them up and as they ob-
tained their heat from the coal, all the coal's heat did not go into
the boiler to make steam, but some was lost up the chimney.

Now, if 20.75 lb. of air were fed per pound of coal, instead of
only the required 10 lb., double the quantity of gases would
pass from the boiler.   And as these gases would escape up the
chimney at about the same temperature as the 10.75 lb., the
heat loss would be about double that in the first case.   This is
true because with equal temperature the heat contained in 21.50
lb. of gas is just double the amount contained in 10.75 lb.

Thus, it is important to discover just what amount of excess
air is most economical under the existing conditions in your
plant and in order to know this some means must be employed
to measure or calculate the air supply to the boiler.

ESTIMATING AIR SUPPLIED

Direct measurement would be difficult to make and unsatis-
factory in accuracy.   A far easier and more accurate means is to

analyze the flue gases and calculate the air supply from this analysis and the coal analysis. Flue-gas analysis is also useful in checking boiler operation from day to day so as to be sure conditions will remain economical.

Somehow or other, flue-gas analysis has a very mysterious and forbidding sound. People are inclined to think it is too deep and dark for them to understand and, consequently, many have not made the good use of it that they should. As a matter of actual fact, it is simple to understand and easy to master.

APPARATUS REQUIRED

A suitable apparatus is required for making a flue-gas analysis. Numerous types are on the market all of which have points of merit. Most of them, however, are based on the Orsat apparatus which was designed by a man of that name. For this reason, the principle and operation of the Orsat only will be given here.

Following is a list of the essentials of a flue-gas analyzing outfit:

1 standard Orsat-Muencke flue-gas analysis apparatus.....	$20.00
2 rubber gas bags for pipettes @ 50c. each...............	1.00
2 large glass bottles, @ 50c. each......................	1.00
2 rubber corks for bottles @ 15c. each..................	0.30
10 ft. antimony rubber tubing ($\frac{1}{4}$ in.) @ 10c..............	1.00
10 ft. of $\frac{1}{4}$ in. glass tubing in 5-ft. lengths @ 2c.........	0.20
4 Mohr's pinch cocks @ 8c. each........................	0.32
1 German-glass funnel (2-in. size)......................	0.10
1 lb. caustic potash (purified sticks)....................	0.35
$\frac{1}{4}$ lb. pyrogallic acid..................................	0.80
1 lb. commercial copper oxide.........................	0.55
1 lb. muriatic acid...................................	0.30
10 ft. copper wire No. 10 gage @ 10c...................	1.00
Total......................................	$26.92

The Orsat determines the percentages by volume of carbon dioxide (CO_2), carbon monoxide (CO), and oxygen (O_2) in the flue gases. It consists chiefly of three bottles (pipettes) connected to a common header. One contains caustic potash for absorbing the CO_2, one potassium pyrogallate for absorbing the oxygen, and one acid cuprous chloride for absorbing the CO.

A bottle of water is used for forcing the sample into and out of
the pipettes, and a burette is provided for measuring in cubic
centimeters the percentage of the respective gases contained in
the sample of flue gas.

Unpacking and Assembling Apparatus

The Orsat apparatus is shipped knocked-down; that is, the glass
parts are taken out of position and securely packed so as to avoid
breakage. The first thing to do, then, is to get the apparatus
properly put together again. If you purchase an Orsat-Muencke,
the following directions will serve as an exact guide. If you
happen to purchase some other type these directions may have to
be modified slightly, but the modifications will be self-evident
when you come to examine the parts. The directions I will give
for preparing the chemicals and operating the apparatus can be
followed exactly with any of the standard types of Orsat.

After carefully unpacking the box in which the apparatus is
shipped and making sure that you have not missed anything, dust
off the cabinet and wash the glass parts with warm water and soap,
rinsing thoroughly in clean water at the end. Take both front
and back slides out of the cabinet and place it before you so that
the long, narrow compartment is at the right.

Next, put the header A, Fig. 12, in position, first making sure
that the five rubber connectors B are in place ready to make the
connection between the header and the other parts. The header
is held in place by the small wooden latch C; be sure that this is
in the closed position before proceeding.

The next step is to fit the burette or measuring chamber D
into position. This burette is provided with an outer case E, of
glass, for the purpose of preventing error due to change in the
temperature of the air in the room affecting the gas in the burette.
The space between the outside case and the burette should be
filled with clean water. As the rubber corks F both contain vent
holes, the one in the bottom cork will have to be plugged up after
the water is run in. See that the white side of the case with the
blue stripe down the middle comes on the side opposite to the

scale marks on the burette. This white and blue background makes it easier to read the water level in the burette when measuring.

Having the casing filled with water, the next step is to connect the burette with the header at the top. Put the two small sliding shelves G over the stems H and H' and fit the shelves into their grooves. This will hold the burette in position so that you can
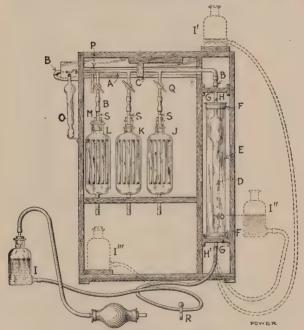
FIG. 12.—Diagram for assembling orsat.

use both hands for slipping the rubber connector over the stem. Be sure that the stem is moistened with water as this will make the rubber slide much more easily. Draw the top shelf out a little so that the stem does not come directly under the header end, then gently work the rubber connector over the stem until it fits snugly with the weight of the burette resting on the bottom

shelf. This will keep strain off the header. Great care will be
necessary in the making of these connections as the use of too
much force will result in breakage.

Two pieces of rubber tubing come with the apparatus. The
longer piece is for making the connection between the burette
and the leveling bottle I. Before making this connection, slip
one of the pinch cocks on the tubing, as this will come in handy to
regulate the water level when making analyses.

Next, the pipettes J, K and L are put into place. These
pipettes consist of two bottle-like parts connected at the bottom
by means of a glass neck. The construction of the pipettes
varies somewhat with different apparatus. Some, such as J
and K, have the stem M.connected solidly to the bottle part while
with others, such as L, the stem forms part of a stopper which
makes a ground-glass fit with the neck of the bottle part.

A number of small glass tubes are furnished to insert in the front
leg of each pipette. These tubes may come already in place.
If so, there may be some cotton wedged into the bottle above
them to prevent them rattling and possibly becoming broken in
shipment. This cotton must all be removed. If the tubes do
not arrive already in place fill the front leg of two pipettes as full
as you can with the plain tubes and the front leg of the third
pipette with the tubes which have little spirals of copper wire in
them. Be sure that the pipettes are arranged in the cabinet in
the proper order; the two nearest to the burette should contain
the plain glass tubes while the farthest one should contain the
tubes with the copper spirals. In time these copper spirals will
become dissolved by the solution used in this pipette and new
tubes containing spirals will have to be purchased and put in.

Into the back leg of each pipette fit a goose-neck stopper, as
shown in Fig. 13, and to the goose-necks of the two pipettes
furthest away from the burette attach the rubber gas bags, as
shown in Fig. 14. The object of these bags is to prevent air from
coming in contact with the chemicals in the pipettes and spoiling
them. The chemical in the first pipette need not be so protected.

The U-tube O, Fig. 12, is next attached to the end of the header,

-as shown, and the apparatus is ready to load and use. This
U-tube has a wad of mineral wool in its open end and serves as a
filter for the gases before they enter the apparatus, catching any
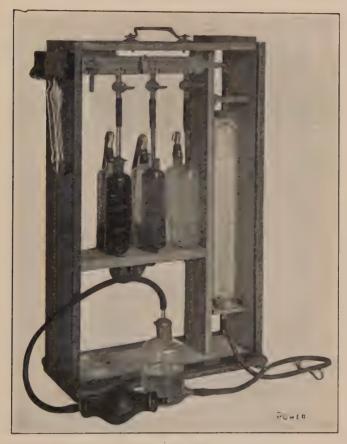
FIG. 13.—Front view of assembled apparatus.

particles of dust and soot which might otherwise foul up the header
and cause trouble in the glass cocks. It also can be filled with

small lumps of calcium chloride for absorbing moisture from the
gases.   This, however, is not absolutely necessary.

I would advise all beginners to practice loading and manipulat-
ing the apparatus with plain water before putting in the chemi-

Fig. 14.—Rear view of assembled apparatus.

cals, as the latter are nasty to spill or slop around as well as
somewhat too expensive to deliberately waste.   So, until you

fully understand how the analysis is conducted, plain water is the safest and cheapest material to experiment with.

LOADING APPARATUS

The correct amount of chemical must be put into each pipette or otherwise the apparatus will not work well. Remove the goose-neck from the rear leg of the pipette and add the chemical through the glass funnel until the two legs are slightly more than half full. In order that the liquid may rise equally in both legs the stop cock in the front connection must be open and also the three-way cock P in the header, Fig. 12, must be open to the atmosphere. After you have filled one pipette J, for instance, tested it and found it to contain the proper quantity of liquid, it is an easy matter to get the other two correct simply by filling them to the same level.

To test whether pipette J contains the right quantity of liquid, fill the leveling bottle I about two-thirds full of water, first closing the pinch cock R. See that all the glass cocks connecting with the header are closed except cock Q, which must remain open. Now, raise the leveling bottle and place it on top of the cabinet as at I'. Then, press the buttons of the pinch cock R until the water begins to rise in the burette. This places the air trapped above the water in the burette and in the header under a slight pressure and as the stop cock Q is open this pressure is communicated to the front leg of the pipette J, driving the liquid down in this leg and up in the back leg. By regulating the pressure of your fingers on the pinch cock R you can control the flow very nicely. If the pipette contains the correct amount of liquid, by the time the liquid has gone down in the front leg to the point where the body part begins to narrow into the bottom-connecting tube, the liquid in the back leg will have risen to the point where the body part begins to narrow into the neck at the top.

If too much liquid has been put into the pipette, the back leg will be full or overflowing before the front leg has been emptied to the

point mentioned in the preceding paragraph, and some of the liquid will have to be removed. If not enough liquid has been put in, air will force its way through the bottom connection and bubble up through the liquid in the back leg. To prevent this, more liquid must be added.

EMPTYING PIPETTES

After the apparatus has been used for some time, the chemicals become weak and must be renewed. A convenient way of emptying a pipette is to fill a short length of rubber tubing (about 2 ft. long) with water, and while holding your finger over one end, to prevent the water from running out, put the other end into the back leg of the pipette. Then, lower the free end into a sink or basin so that this end is somewhat below the other and release your finger, when the liquid will all siphon out of the pipette.

PREPARING FOR AN ANALYSIS

After all three pipettes have been properly filled and tested the apparatus is almost ready for making analyses. Before it is quite ready, however, the liquid in each pipette must be drawn up into the front leg until this leg is full to the fine black ring, which will be found around the neck at S.

To do this in the case of pipette J, notice whether the water level in the burette D is near the top. If it is not, close all the header-connection cocks except the threeway cock P, which must be open. Then, raise the leveling bottle to I' and allow the water level to rise in the burette by opening the pinch cock R. When the water level in the burette is right, close the three-way cock and open stop-cock Q. Lower the leveling bottle to the table and by releasing pinch cock R allow the water in the burette to run back into the bottle; while doing so, watch the liquid rise in the front leg of J. When this is near the top, proceed very slowly and carefully as the necks M (made of what is known as capillary tubing) have a very fine bore, and if you allow the liquid to rise

too rapidly when near the top, there is considerable danger that it will shoot up into the header and over into the burette before you can check it. While this will do no harm when practising with water, it is undesirable when dealing with the chemicals, as it makes the water in the burette more or less capable of absorbing the flue gases, thus causing error, and it reduces the quantity of liquid in the pipette so that trouble may arise in this direction also.

The proceeding for bringing the liquid in pipettes K and L up to the mark is exactly the same as for pipette J, only, while doing so, it is advisable to remove the goosenecks with the rubber bags attached, from the mouth of the back legs, for unless there happens to be enough air in these bags, a vacuum may be formed over the liquid in the back leg, thereby preventing it from coming fully up to the mark in the front leg as it should. As soon as the liquid has been brought up to the mark, replace the goosenecks and rubber bags to prevent further contact with the outside air. When dealing with the chemicals, the air that it trapped in the back leg of K and L will lose its oxygen, and, hence, shrink in volume so that a slight vacuum will be formed. When this noticeably interferes with the operation of the apparatus, remove the gooseneck for an instant to let in a little more air. Be sure to do this, however, when the liquid is up to the mark in the front leg or when the gas bag is perfectly flat or empty, as otherwise, instead of letting more air into the system, you will really let some out and cause a worse vacuum than ever.

A better way to avoid trouble from the formation of a vacuum is to force a little excess air into the bag by blowing into it with your mouth, then, pinching the neck to hold the air in until the connection is made. It is well to take precaution, however, when doing this, and be sure that there is none of the chemical on the end you put to your lips, as otherwise you may burn yourself.

With the liquid in all pipettes properly adjusted, an analysis can now be made. That is, we can go through the motions of making an analysis. Later, when more practice has been gained, we will load with the proper chemicals and after making

suitable arrangements for obtaining a sample of the flue gases, we
will be prepared for actual work.

VOLUME OF SAMPLE

For the present, assume that the filter O is connected with the
supply of gas. Our sample will consist of 100 c.c. of flue gas at
atmospheric pressure and at the temperature of the ordinary room
air.

At its lower part, where all our readings will be taken, the
burette is graduated in cubic centimeters with a subdivision for
each 0.2 of a cubic centimeter. Thus, the figures of the scale read
direct in per cents. and decimal fractions of a per cent.

A cubic centimeter is another French or metric unit employed
because of its great convenience, like the gram, decigram and milli-
gram in our proximate coal analysis. The metric units of length,
corresponding with inches, feet and yards, are the centimeter,
decimeter and meter. Consequently, the units of volume are the
cubic centimeter, cubic decimeter and cubic meter. Do not fall
into the mistake, however, of assuming that 100 c.c. equals 1
cu. m. for they do not—no more than 12 cu. in. equal 1
cu. ft. At the bottom of the scale on the Orsat burette you
will find the letters c.c., which is the standard abbreviation for
cubic centimeter.

EFFECT OF TEMPERATURE AND PRESSURE

You may have noticed that I specified that our gas sample was
to be at a certain pressure and temperature. This is because the
volume of a gas is greatly influenced by changes in pressure and
temperature. Hence, we must be careful to have conditions
uniform throughout an analysis, or error will result. It is advis-
able for best results to locate the apparatus where no drafts will
blow on it and where the temperature of the air does not change
rapidly.

To illustrate how important an influence temperature and pres-
sure have, two simple experiments can be made with your Orsat.

To show the effects of change in temperature, locate the

apparatus in a warm spot and allow it to remain there for about an hour, until the glass work and the water come up to the temperature of the air. Then, with all cocks closed except P, which must be open, slowly raise or lower the leveling bottle, using the side of the cabinet as a guide, until the water level in the burette D is exactly on the zero mark, while at the same time the water level in the bottle is at the same height as the water level in the burette, as shown by the position of the bottle at I''. Then, using care not to change the level of the bottle, close cock P. To make sure that no mistake has been made while closing the cock P, check the water levels once more by noting whether both are at the level of the zero mark. If not, and if they cannot be brought right by a slight raising or lowering of the bottle, open the cock P and start all over again.

Having thus succeeded in getting the correct quantity of warm air into the burette, place the leveling bottle in its cleat within the cabinet at I''' and shift the apparatus to some spot where the temperature is 10 or 15 deg. cooler. After about an hour's time, test the water level again (without opening cock P) by slowly raising and lowering the leveling bottle at the side of the cabinet until the level in the bottle is the same as the level in the burette. This new level will be considerably above the zero mark, showing that the reduction in temperature caused the volume of the air in the burette to shrink. A reduction in temperature of 10 deg. means a reduction in volume of about 1.8 per cent.

To show the effect of change in pressure, open cock P and by raising or lowering the leveling bottle, draw in enough air to bring the water level to about the 10 per cent. mark. Close cock P and make an accurate reading by raising or lowering the bottle until the water level is the same in the bottle and in the burette. Now, if you raise the bottle, say, to position I', the water level in the burette will rise almost to the 14 per cent. mark. This shows that the tendency of the water in the bottle to flow into the burette and seek its own level has put an increase of pressure on the air trapped in the burette and, hence, has reduced its volume by compression.

MANIPULATION OF THREE-WAY COCK

Thus far, I have said nothing about the manipulation of the three-way cock P. Its correct manipulation is very important when making an actual analysis, and as a poor understanding of how it should be handled would undoubtedly lead to confusion and inaccuracy in results, it is worth devoting a paragraph at this point to this important part of the machine.

Fig. 15 is a diagram of the three-way cock connection. The straight-run passage XY is parallel with the handle of the cock and the branch connection Z is on the same side as a dark dot found on the handle. In the position shown in Fig. 15 (in which position the handle would be horizontal and the dot would be facing down) the gas supply, the outside air and the burette, would all be connected.

In the reverse position (with handle horizontal and dot facing up) only the gas supply and the burette would be connected.
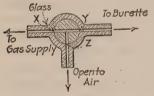
FIG. 15.—Diagram of three-way cock.

With the handle in a vertical position and the dot facing to the left the gas supply and the outside air would be connected. With the handle vertical and the dot to the right, the burette and the air would be connected. With the handle in any 45-deg. position no connections would be open.

Assume that the apparatus is conected with the gas supply. Connect the burette with the atmosphere by setting the three-way cock with the dot on the handle facing to the right. Then, place the leveling bottle on top of the cabinet and drive all the air out of the burette by opening the pinch cock R, Fig. 9, and allowing the water to run in until it reaches the 100-c.c. mark on the upper neck H. Now, turn the three-way cock so that the dot faces up, thus connecting the burette and gas supply. Lower the leveling bottle and release the pinch cock R entirely from the rubber connection. Then, connect the small hand pump to the

leveling bottle in the manner shown in Fig. 12 and start pumping. If the gas is being drawn direct from the flue or chimney be sure that you pump long enough to secure a burette full of true gas. The amount of pumping required depends upon the length of the connection between the apparatus and the flue. After a little experience you will be able to tell just about how much pumping is required. Remember, however, it is far better to pump a little longer than is actually necessary than not to pump quite long enough. If the gas is being drawn from some kind of collecting apparatus, only a few strokes of the pump will be needed—say, a half dozen.

When you feel sure the burette is full of real gas, cease pumping and immediately give the three-way cock one-eighth turn to the right so that the handle is at 45 deg. and the dot is still on the upward side. Then, put the pinch cock on the leveling-bottle hose at about 6 in. from the burette end, disconnect the hand pump, and place the bottle on top of the cabinet. Now, open the three-way cock to the air by giving it another eighth turn to the right and by carefully releasing the pinch cock from the leveling-bottle hose, run the water into the burette to exactly the zero mark. If, by accident, you permit the water to rise above the zero mark, do not attempt to bring it back by means of the leveling bottle, for this would only let air into the burette and spoil the sample. If you wish, you can proceed with the analysis and make correction by calculation afterward, but I consider it better to simply expel all the gas and start over again. This avoids chance for error later and is about as quick as if you took the time to calculate the correction.

Testing for CO_2

As soon as the water is brought up to the zero mark, close the three-way cock by giving it an eighth turn to the left, and open the cock Q, on the first pipette. Squeeze the pinch cock on the leveling-bottle hose and allow the water to rise in the burette to or nearly to the 100-c.c. mark. This forces the gas over into the

pipette J, the gas driving the liquid from the front leg of the pipette into the back.   All the little glass tubes in the front leg are now exposed to the gas and as they are dripping with the solution just driven out, they present a large wetted surface, and, hence, hasten the chemical action between the solution and the gas.

Allow the gas to remain in the pipette about one minute, then draw it back into the burette by lowering the leveling bottle and releasing the pinch cock, using care that none of the solution is drawn over with it.   Repeat this operation about three times and then measure the gas as follows: Draw the solution in the pipette up to the mark S on the stem and close the cock Q.   Then, release the leveling-bottle hose entirely from the pinch cock and make the water level in the burette and bottle equal by raising or lowering the bottle at the side of the cabinet as before described.   Read the mark at which the water now stands in the burette.   If, for instance, the water now stands at the 8.2-c.c. mark, the volume of the gas has diminished 8.2 c.c. in 100, or 8.2 per cent., and that is the percentage of CO_2 in the flue gas.   The solution in the first pipette takes out (or absorbs) the CO_2, leaving the oxygen, carbon monoxide and nitrogen.

Checking Results

After making the reading, run the gas into the pipette once more and take another reading as a check to make sure that all the CO_2 has been absorbed.   If both readings are the same, all right.   If not, make one more trial.   When reading for CO_2 you should have no trouble in getting the first two readings to agree.   If you do have trouble, your method may be wrong and it may be necessary to allow the gas to stand in the pipette a little longer each time or to increase the number of times you run it back and forth.   Or, if the solution has been used a long time it may have become weak and need renewing.

A good thing to remember when running the gas from the burette into the pipette and *vice versa* is to watch the rising liquid,

in this way eliminating the danger of running any liquid out of the vessel in which it belongs. Thus, when running the gas from the burette into the pipette, watch the water rise in the burette, stopping the flow before it shoots up through the neck H, and over through the header into the pipette. When running the gas back, watch the liquid rise in the front leg of the pipette and stop it before it reaches the burette.

TESTING FOR OXYGEN

After getting a check on the CO_2 reading, open the cock on pipette K, and run the gas back and forth in this pipette in exactly the same manner as before. Only, instead of running it in and out only four times, as in the case with the first pipette, the operation should be repeated about seven times before a reading is taken. The reason for this is that the solution for absorbing oxygen, the part of the flue gas absorbed in the second pipette, does not act as quickly as the solution used in the first pipette for absorbing CO_2.

Check the reading in the same manner as before by running the gas over once more and taking an extra reading. The difference between the new correct reading and the first correct reading gives the percentage of oxygen contained in the flue gas. For instance, if the new reading were 17.6 per cent. and the previous one had been 8.2 per cent., then the oxygen content in the flue gas would be

$$17.6 - 8.2 = 9.4 \; per \; cent.$$

TESTING FOR CO

After obtaining a correct reading for the oxygen, open the cock on pipette L and go through the same process with this pipette as with the other two, only repeat the operation of running the gas back and forth about 11 times. The solution in this pipette absorbs any carbon monoxide (CO) that may be contained in the flue gas. Its action, however, is very slow and feeble and much care and patience must be used to get a correct reading.

The principle upon which the Orsat apparatus is based is that when certain chemical solutions are brought in contact with certain gases, the gases combine chemically with the solutions in such a way that they become a part of the solution. Ordinary flue gas consists principally of a mixture of carbon dioxide, oxygen and nitrogen and, sometimes, carbon monoxide, hydrogen and some hydrocarbons. When a given volume of such a mixture is brought in contact with a solution of caustic potash and water, the carbon dioxide combines with the caustic potash and forms a substance which becomes a part of the solution. The solution increases in volume but very slightly indeed—so slightly, in fact, that the increase may be entirely neglected in our work. But the volume of the flue gas has diminished by the amount of carbon dioxide it contained.

In a similar way the oxygen and the carbon monoxide disappear from the flue gas when brought into contact with the proper chemical solutions.

The solutions used in the Orsat must be employed in the order here given because the solution for carbon monoxide will absorb oxygen as well, and the solution for oxygen will absorb carbon dioxide, so the CO_2 must be taken out first, the oxygen second and the CO third.

Solution for CO_2

The solution for the first pipette, to absorb the CO_2, is caustic potash (chemical name, potassium hydrate) dissolved in the proportion of 1 lb. of caustic to $2\frac{1}{2}$ lb. ($2\frac{1}{2}$ pints) of water.

Perhaps the most convenient method is to mix up $\frac{1}{2}$ lb. of the caustic at a time. A good way to do is to fill an ordinary 1-quart milk bottle about five-eighths full of water and add half of the sticks in a 1-lb. package of caustic. If you have a pair of reasonably accurate small scales, you can weigh the bottle and then add the required $1\frac{1}{4}$ lb. of water, thus securing greater accuracy than guessing at five-eighths of a quart. A half pound of caustic will make a little more than enough solution

for five loadings of the pipette. And one loading of the pipette is sufficient for about 325 analyses where the percentage of CO_2 extracted each time is 12 per cent. Thus, one loading should last from three months to a year or more, depending on how often the apparatus is used. The bottle containing the unused part of the mixture should be carefully labeled, fitted with a cork or cover and stored away in a safe place. It is safest to handle the potash sticks with tongs rather than with the bare hands because while no harm will be done if both the sticks and your hands are dry, a disagreeable burn results if either happens to be moist. Use care in handling the solution when made up because a drop on the flesh will burn and a drop on clothing, shoes, etc., will eat a hole.

Solution for Oxygen

The solution for the second pipette, to absorb the oxygen, is potassium pyrogallate; made by mixing pyrogallic acid (which comes in the form of a powder) with a suitable quantity of the caustic-potash solution just described. As this solution absorbs oxygen it will quickly lose strength if exposed to the air; hence it must be sealed up as soon as possible.

A good way to mix the solution is to put 1 oz. of the pyrogallic acid into a quart bottle, pour in about a pint of the caustic solution and immediately seal the bottle air-tight.

After loading the pipette, place the gooseneck and rubber bag on the back leg as quickly as possible to exclude the air. One loading of the pipette will absorb about 200 c.c. of oxygen. Thus, if the average amount of oxygen in the flue gases analyzed is, say, 8 per cent., the solution would be good for about 25 analyses.

Solution for CO

The solution for the third pipette, to absorb the CO, is acid cuprous chloride. This can be most conveniently made as follows: Put enough copper oxide into a quart bottle to make a layer on the bottom $\frac{1}{4}$ in. thick. Put in ten or a dozen lengths of No. 10 gage copper wire, bare and clean, cut in lengths to reach from the top to the bottom of the bottle. Then fill the bottle

with hydrochloric acid (hydrochloric acid is simply equal parts
water and muriatic acid). Seal the bottle air-tight and shake it
occasionally to hasten the reaction. When the solution turns
nearly colorless (after about 48 hr.) it is ready to use. After
some of the solution has been taken out to load the pipette,
immediately add more hydrochloric acid so as to keep the bottle
full all the time. As the copper wire and copper oxide gradually
disappear, add some of each from time to time so as to constantly
keep about the usual amount in the bottle.

As this solution also deteriorates when exposed to the air, be
sure to connect the rubber bag to the pipette as soon as it is
loaded. One loading of the pipette will absorb about 100 c.c.
of CO; hence it would be good for about 100 analyses where the
amount of CO in the flue gas averaged 1 per cent.

When any of the solutions begin to show signs of weakness
they should immediately be renewed regardless of the length of
time they have been in use.

Taking the Sample

The best place from which to take the sample of flue gas is
from the last pass, if the boiler is a water-tube, or from the
connection between boiler and breeching if a fire-tube. Cut a
length of $\frac{1}{2}$-in. pipe T, Fig. 16, long enough to extend half way
across the gas passage and project out about 6 in. at one side.
Fit an elbow and vertical connection to this as shown. The pipe
T may be inserted either through a drilled hole or through some
existing opening. In either case, stop up the hole or opening
around the pipe with waste or plastic asbestos so as to prevent
the danger of air leaking in and spoiling the sample. Be sure
that the piping is made up air-tight. Draw the end U down so
that $\frac{1}{4}$-in. rubber tubing can be pushed over it.

If instantaneous flue-gas readings are wanted, connect the
Orsat and the end U by a length of rubber tubing and proceed
to draw in the sample as before directed.

If a sample representing a certain period of operation is de-
sired, an arrangement, such as shown in Fig. 16, may be used.

Obtain two large bottles, such as those in which spring water is sold, and fit them with rubber corks, each perforated for two glass tubes. These corks can be secured from the dealer who sells you the flue-gas apparatus. Then, fit each bottle with one long glass tube and one short one in the manner shown. If the top
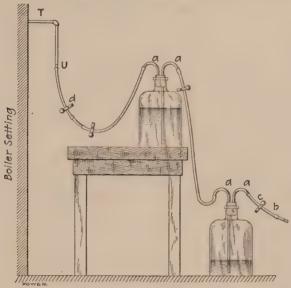
FIG. 16.—Arrangement for collecting a time gas sample.

of each glass tube is heated and bent over, as shown at *a*, the rubber tubing is not so likely to kink up and stop the flow of water.

Fill one bottle full and the other about one-eighth full of water. Connect the long tube of each bottle with a length of rubber tubing about 6 ft. long; connect each short tube with a length of rubber tubing about 12 to 18 in. long and in the end of these short lengths insert a glass-tube nipple, 4 to 6 in. long as shown.

Arrange the bottles one above the other, as shown in Fig. 16, and let water siphon into the lower bottle until it is full and water

begins to run out at *b*. Then, set pinch cock *c* and reverse the bottles, connecting *b* with the tubing *d*. Before doing this, however, apply the small hand pump, which comes with the flue-

FIG. 17.—Arrangement of sampling bottles and apparatus.

gas apparatus, to the end of the tubing *d* and expel all the air in the piping; then, set a pinch cock on *d* as close to the lower end as possible. If these directions are followed closely, very little or no air will get into the system to make the sample unfair.

Now, release all pinch cocks and allow the water to siphon

from the upper to the lower bottle. This causes a vacuum in the upper bottle which draws in the gas from the boiler.

By heating the end of one of the long glass tubes and drawing it down to a finer opening, a longer time will be required to siphon the water over and hence to fill the upper bottle with gas. If, for instance, an 8-hr. sample is desired, a little experimenting with the size of opening in the glass tube will result in getting the time of water flow about correct. Of course, as it is not necessary to have more than perhaps a quarter of a bottle full of gas, the length of time required for the water to siphon over does not matter much, provided it is longer than the length of the test desired.

When the desired gas sample has been drawn into the upper bottle, set all pinch cocks and arrange the bottles, as shown in Fig. 17, the one full of water slightly higher than the other. With this arrangement the gas is under a slight pressure and if the system is accidentally opened, gas will escape, but no air will leak in to spoil the sample. Connect the gas bottle with the flue-gas apparatus, as shown, and proceed with the analysis as explained in previous paragraphs.

As water aborbs CO_2, the water in the collecting bottles should be saturated with gas before samples for testing are collected. This can be done by drawing some gas first into one bottle, then into the other and allowing it to stand for some time, shaking the bottles now and then to induce complete saturation.

Care of Apparatus

In course of time the rubber tubing and connections used with the Orsat will become hard and crack, when they will need renewing.

The caustic will affect the glass pipettes. Hence, if the apparatus is not to be used for some length of time, it is well to empty the apparatus before storing it away.

The glass stop cocks must be kept clean or they will not remain air-tight. Also, if they are not lubricated frequently, they may become stuck and cause trouble. A good lubricant to use is vaseline. This point should be attended to frequently if trouble is to be avoided.

CHAPTER IV

HEAT LOST IN FLUE GASES

HEAT LOST UP THE CHIMNEY

When a pound of fuel is burned under a boiler its available heat is distributed in a number of ways. The largest part is transferred to the water within the boiler and converts some of it into steam. But from 20 to 60 per cent. is lost in various ways. The greatest loss is due to the heat carried up the chimney by the flue gases, and, as this loss depends to a large extent upon the skill and care employed in operation, it is one in which every engineer should be greatly interested and about which he should be thoroughly posted.

If after a pound of flue gas has come in contact with the heating surface of the boiler and has given up some of its heat to the water within, it passes out to the chimey at, say, 500 deg. F., how much heat is lost or carried up the chimney?

All the heat that the gas contains, over and above what the air and coal from which it was formed contained, was derived from the combustion of the coal. Then to all intents and purposes the heat lost with every pound of flue gas, expressed in B.t.u., must be the product of the number of degrees difference in temperature between the air entering the furnace and the flue gas going out of the boiler, multiplied by the heat required to raise the temperature of a pound of flue gas 1 deg.

SPECIFIC HEAT

This brings us to a consideration of "specific heat," a term often employed in steam engineering. By definition, the amount of heat required to raise the temperature of a pound of water 1 deg.

is one B.t.u.   A pound of air requires about one-fourth as much heat as a pound of water for a rise of 1 deg., and a pound of iron requires only about one-eighth as much as water.   The quantity of heat required to raise the temperature of a given amount of substance a given number of degrees depends upon the nature of the substance and is different in almost every case.   Hence, in problems involving quantity of heat and quantity of materials, it is often important to know the amount of heat required to cause a rise of 1 deg. in temperature per pound of material under consideration.   This quantity is called the specific heat of the substance.   Thus, the specific heat of iron is said to be 0.13, because a pound of iron requires 0.13 B.t.u. to raise its temperature 1 deg.

The specific heat of flue gas is not exactly known, nor is it uniform for all temperatures.   That is, at low temperatures it is somewhat less than at high.   However, the most commonly accepted value is 0.24, and hence this is the one we will use.

Estimating Heat Lost in Flue Gases

The heat lost or carried up the chimney by the flue gases per pound of fuel burned can be estimated by multiplying the weight of the gases generated per pound of fuel by the specific heat of the gases and the difference in temperature between the gases leaving the boiler and the air entering the furnace.   The answer expresses the loss in B.t.u.   This calculation can be written as a formula, thus:

$$L = 0.24 \ W \ (T - t),$$

where

L = B.t.u. lost up chimney per pound of fuel burned;

0.24 = specific heat of the flue gases (or the amount of heat required to raise 1 lb. of the gases 1 deg.);

W = weight of flue gases formed per pound of fuel;

T = temperature of gases leaving boiler, degrees F.;

t = temperature of air entering furnace, degrees F.

Weight of Gases per Pound of Fuel

To make the foregoing calculation it is necessary to know the weight of flue gases formed per pound of fuel burned. This is found by the following formula, which looks worse than it really is:

$$W = 3.032 \, C \left(\frac{N}{CO_2 + CO} \right) + (1 - A)$$

where

W = weight of flue gases formed per pound of fuel burned;

3.032 = a constant;

C = decimal part by weight of carbon (total carbon) in the fuel as fired;

N = percentage by volume of nitrogen in the flue gases;

CO_2 = percentage by volume of carbon dioxide in the flue gases;

CO = percentage by volume of carbon monoxide in the flue gases;

A = decimal part of weight of ash in the fuel as fired.

The proximate coal analysis does not show the decimal parts proportion or percentage, of total carbon in the fuel; it only show, the percentage of fixed carbon. Consequently, in order to use the foregoing formula, we will have to estimate or guess at the amount of carbon contained in the volatile matter, add this to the amount of fixed carbon and consider the sum as being the amount of total carbon in the fuel. The accompanying chart, Fig. 18, developed by Professor Marks and originally published in POWER for Jan. 14, 1913, will give results close enough for our purpose.

Estimating Total Carbon in Coal

To calculate the carbon in the volatile, add together the percentage of fixed carbon and volatile matter as shown by the proximate analysis and divide this sum into the percentage of volatile matter. The quotient multiplied by 100 gives the percentage of volatile matter in the combustible. Having found

this, locate a corresponding point on the scale at the bottom of the chart and trace an imaginary line straight up to the curve and then horizontally to the scale at the left margin which gives the per-
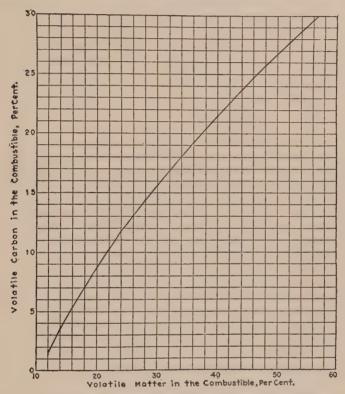
FIG. 18.—Chart for determining the carbon in the volatile matter.

centage of volatile carbon in the combustible matter. Multiply the percentage thus formed by the percentage of combustible in the coal and divide by 100 to obtain the percentage of volatile carbon in the coal. Add this percentage to the percentage of fixed carbon in the coal as shown by the proximate analysis to obtain the total carbon in the coal.

To illustrate with a numerical example, assume that we wish to estimate the percentage of total carbon in a coal with this analysis: Moisture, 6.2 per cent.; volatile matter, 16.8 per cent.; fixed carbon, 70.7 per cent.; ash, 6.3 per cent. The sum of the percentage of fixed carbon and volatile matter is

$$70.7 + 16.8 = 87.5$$

and this, divided into the percentage of volatile matter and multiplied by 100, gives

$$\frac{16.8}{87.5} \times 100 = 19.2 \; per \; cent.$$

volatile matter in the combustible.

Locating the 19.2 point on the scale at the foot of the chart and tracing an imaginary line straight up to the curve and over to the margin we get 8.2 as the percentage of volatile carbon in the combustible. And this multiplied by 87.5, the percentage of combustible matter in the coal, and divided by 100, gives

$$8.2 \times 87.5 \div 100 = 7.2$$

the percentage of volatile carbon in the coal, which added to the percentage of fixed carbon in the coal gives

$$70.7 + 7.2 = 77.9$$

the percentage of total carbon in the coal.

ESTIMATING NITROGEN

The flue-gas analysis as made according to the directions given in previous chapters gives the percentage by volume of carbon dioxide (CO_2), oxygen (O) and carbon monoxide (CO). In addition to these there exists water, in the form of superheated steam, nitrogen and sometimes hydrogen and various hydrocarbons. The steam condenses and only a little of it gets to

the flue-gas apparatus. All the other constituents except the nitrogen form a small percentage of the total volume. Partly because of this fact and partly because it is difficult to detect and measure them, they are usually ignored entirely. Thus, the difference between 100 and the sum of the percentages of CO_2, O and CO is taken as the percentage of nitrogen (N) contained in the flue gas.

To illustrate, if the flue-gas analysis shows 11 per cent. CO_2, 8 per cent. O and 0.8 per cent. CO, the percentage of nitrogen in the flue gas would be taken as

$$100 - (11 + 8 + 0.8) = 80.2$$

This practice is followed because there is no liquid or chemical solution capable of combining and absorbing nitrogen like CO_2 O and CO are combined and absorbed.

With equal temperature and pressure CO_2 has the same volume as the oxygen required for its combustion. That is, if it requires 30 cu. ft. of pure oxygen at a certain temperature and atmospheric pressure to completely burn a pound of pure carbon the CO_2 formed will have a volume of just 30 cu. ft. when cooled down to the temperature at which the oxygen was measured. The volume of carbon monoxide is twice that of the oxygen required in its formation. Thus, the sum of the percentage of CO_2 and O and one-half the CO should always equal 21 (the percentage by volume of oxygen in the air) when carbon alone is the combustible. But in the average plant carbon is rarely the only combustible in the fuel; it is almost always accompanied by hydrogen.

When hydrogen burns it forms steam which practically all condenses and never gets to the flue-gas apparatus. Thus, the hydrogen sidetracks the oxygen of the air required for its combustion but leaves the nitrogen to pass on to the flue-gas apparatus along with the nitrogen of the air required for the combustion of the carbon. The result is that the sum of the three oxygen constituents of the flue gas (CO_2, O, CO) do not add up to 21, but to some smaller figure, the exact value of which depends,

of course, upon the quantity of available hydrogen contained in
the fuel.

Using the data given in the last lesson for coal and flue-gas an-
alysis in this lesson, the formula for estimating the weight of flue
gases formed per pound of fuel burned works out thus

$$W = 3.032 \times 0.779 \left(\frac{80.2}{11 + 0.8}\right) + (1 - 0.063) = 17 \; lb.$$

Assuming that the temperature of the gases as they leave the
boiler is 520 deg. F. and that the temperature of the air entering
the furnace is 70 deg., the formula for calculating the heat lost
up the chimney in the flue gases would work out thus

$$L = 0.24 \times 17 (520 - 70) = 1836 \; B.t.u.$$

If the coal in the foregoing illustration had a heat value of,
say, 13,200 B.t.u. per pound, as fired, the percentage of heat lost
with the flue gases would be

$$\frac{1836}{13,200} \times 100 = 13.9 \; per \; cent.$$

Ratio of Air Supplied to Air Required

It is often desirable to know what the ratio is between the
amount of air actually supplied per pound of coal and the amount
theoretically required. This can be estimated by means of the
following simple equation:

$$R = \frac{N}{N - (3.78 \times O)}$$

where R equals the ratio of the air supplied per pound of fuel to
the amount theoretically required and N and O equal the per-
centage by volume of the nitrogen and oxygen, respectively, in
the flue gases, as shown by the analysis.

Using the data previously given the ratio would be

$$R = \frac{80.2}{80.2 - (3.78 \times 8)} = 1.6$$

This means that for every pound of air required by the coal 1.6 lb. was supplied. Hence, the percentage of excess air is

$$\frac{1.6 - 1}{1} \times 100 = 60$$

MEASURING FLUE-GAS TEMPERATURE

Thermometers with a range up to 212 or a little higher are cheap enough that no difficulty need stand in the way of measuring the temperature of the air entering the furnace; that is, the air in the boiler room. But as the temperatures to be measured get beyond 500 deg. F., which is often the case with flue gases, the cost of the pyrometer (the name used for high-range thermometers) begins to be an important consideration. In some plants the expense of purchasing a standard form of pyrometer may not be warranted, in others it may be impossible to show the management the advantage of keeping constant records on the flue-gas temperature. In such cases the engineer may and should for his own benefit provide himself with the means of making an occasional observation of the flue-gas temperature. This he can do at reasonably moderate cost.

FIG. 19.—Sand bomb and thermometer for measuring flue-gas temperature.

HOME-MADE APPARATUS

Numerous means are available but only one will be presented here. The required equipment consists of the bomb shown in Fig. 19 and a chemical thermometer having a range of 1000 deg. F. The latter may be procured of any chemists' glassware supply house at a cost of from $5 to $10.

The bomb consists of a length of 4-in. pipe capped at one end and a length of $\frac{1}{4}$-in. pipe extending through the center, as shown, to serve as the thermometer well. Sand is packed in about the $\frac{1}{4}$-in. pipe and held in place by means of a layes of plastic asbestos at the open end. The length of the piper is determined by the length of the thermometer. The $\frac{1}{4}$-in. pipe should be of such a length that when the thermometer is inserted it will be inclosed as high as the 400-deg. point on the scale. The 4-in. pipe should be 6 in. longer, as shown. A bail of wire or thin, narrow flat iron attached as shown completes the bomb.

When it is desired to take the temperature of the flue gases, the bomb (without the thermometer) is hung in the middle of the path of the flue gases as near to the point at which they leave the boiler as conveniently possible. After a half to three-quarters of an hour the bomb is removed and the thermometer inserted as quickly as possible. In a few seconds the thermometer will indicate the temperature of the sand which will be practically the same as that of the flue gases.

PRACTICE PROBLEMS

From the following data estimate the percentage of excess air supplied to the furnace, the number of B.t.u. carried up the chimney by the flue gases and the percentage of loss based on the heat value of the coal.

Proximate analysis of coal, moisture, 4.5 per cent.; volatile, 18.6 per cent.; fixed carbon, 65.2 per cent.; ash, 11.7 per cent.; B.t.u., 13,160. Flue-gas analysis, CO_2, 6.3 per cent.; O, 11.7 per cent.; CO, 0.4 per cent. Temperature of air in boiler room, 75 deg.; temperature of gases leaving boiler, 515 deg.

If the above coal costs \$3.10 per net ton (2000 lb.) and if under the present conditions 6200 tons are consumed per year what would be the yearly saving effected if the average percentage of CO_2 were raised to 10.7 and the O reduced to 7.3, other conditions remaining the same?

SOLUTION OF PRACTICE PROBLEMS

The percentage of excess air supplied to the furnace may be determined from the formula for calculating the ratio of air supplied to air required, which is as follows:

$$R = \frac{N}{N - (3.78 \times O)}$$

From the data given, N, the percentage of nitrogen in the flue gas, equals

$$100 - (6.3 + 11.7 + 0.4) = 81.6$$

Substituting in the formula gives

$$R = \frac{81.6}{81.6 - (3.78 \times 11.7)} = \frac{81.6}{37.37} = 2.18$$

Thus, 2.18 lb. of air was supplied for every pound theoretically required. Hence, the amount of excess air supplied with each pound required is

$$2.18 - 1 = 1.18 \ lb.$$

This excess amount divided by the required amount and multiplied by 100 gives

$$\frac{1.18}{1} \times 100 = 118 \ per \ cent.$$

excess air supplied to the furnace.

To calculate the B.t.u. carried up the chimney by the flue gases per pound of coal burned it is first necessary to estimate the weight of flue gases formed per pound of coal. And before this quantity can be estimated it is necessary to estimate the decimal part by weight of total carbon in the fuel. The decimal part of fixed carbon is given (expressed as a percentage) in the proximate analysis of the coal, and equals 0.652. To this must be added the decimal part of volatile carbon, which is estimated

in the manner explained by means of the chart in Fig. 18. The sum of the percentages of fixed carbon and volatile matter is $65.2 + 18.6 = 83.8$, and this, divided into the percentage of volatile matter and multiplied by 100, gives

$$\frac{18.6}{83.8} \times 100 = 22.2$$

the percentage of volatile matter in the combustible.

Locating as closely as possible the 22.2 per cent. point at the bottom of the chart, and tracing an imaginary line up to the curve and over to the side scale, we get 10.4, the percentage of volatile carbon in the combustible. And this, multiplied by the percentage of combustible in the coal (83.8) and divided by 100, gives

$$\frac{10.4 \times 83.8}{100} = 8.7$$

the percentage of volatile carbon in the coal. Shifting the decimal point two places to the left reduces this percentage to a decimal fraction. Adding this fraction to 0.652, the decimal part of fixed carbon in the coal, gives

$$0.652 + 0.087 = 0.739$$

or practically 0.74, which is the decimal part of total carbon in the coal.

The formula for estimating the weight of gases formed per pound of coal burned is

$$W = 3.032\ C\ \left(\frac{N}{CO_2 + CO}\right) + (1 - A)$$

Substituting, gives

$$W = 3.032 \times 0.74 \left(\frac{81.6}{6.3 + 0.4}\right) + (1 - 0.117)$$

$$W = 2.24 \left(\frac{81.6}{6.7}\right) + 0.88 = 28.16\ lb.$$

gases formed per pound of coal burned.

The B.t.u. carried up the chimney per pound of coal burned is estimated by this formula.

$$L = 0.24 \, W \, (T - t)$$

Substituting, gives

$$L = 0.24 \times 28.16 \, (515 - 75)$$
$$L = 6.76 \times 440 = 2974 \; B.t.u.$$

carried up the chimney by the flue gases per pound of coal burned.

The percentage of loss is the number of B.t.u. carried up the chimney per pound of coal divided by the heat value of the coal and multiplied by 100, thus

$$\frac{2974}{13,160} \times 100 = 22.6 \; per \; cent. \; loss$$

There are several ways in which the answer to the last problem can be obtained. The simplest, although, perhaps, not the shortest, is to find the percentage of heat loss in the second case and subtract this loss from the loss we have already worked out for the first case. The difference, divided by the heat value of the coal, will represent the percentage of coal saved per year. Then, the number of tons thus shown to be saved, multiplied by the cost per ton, will give the annual saving in dollars and cents.

First, using the formula for the weight of flue gases formed, gives

$$W = 3.032 \times 0.74 \left(\frac{81.6}{10.7 + 0.4} \right) + (1 - 0.117)$$
$$W = 2.24 \left(\frac{81.6}{11.1} \right) + 0.88 = 17.34 \; lb.$$

the weight of flue gases formed per pound of coal.

Next, substituting this value in the formula for estimating the heat lost up the chimney, gives

$$L = 0.24 \times 17.34 \, (515 - 75)$$
$$L = 4.16 \times 440 = 1830 \; B.t.u.$$

carried up the chimney by the flue gases per pound of coal.

In the first case, 2974 B.t.u. was lost up the chimney per pound of coal.   Hence the saving is

$$2974 - 1830 = 1144 \ B.t.u.$$

per pound of coal.   In percentage this saving amounts to

$$\frac{1144}{13,160} \times 100 = 8.69 \ per \ cent.$$

As 8.69 per cent. of each pound of coal is saved, 8.69 per cent. of each ton and hence 8.69 per cent. of all the coal is saved. Thus, the saving in tons per year equals

$$\frac{6200 \times 8.69}{100} = 538.78$$

and the saving in dollars and cents equals

$$538.78 \times 3.10 = \$1670.22$$

LOSS DUE TO INCOMPLETE COMBUSTION

In one of the early Chapters we learned that carbon under certain conditions will only partially burn, forming carbon monoxide (CO) instead of carbon dioxide (CO_2) and creating only 4450 B.t.u. per lb. of carbon instead of 14,600.   Hence, for every pound of carbon only partially burned

$$14,600 - 4450 = 10,150 \ B.t.u.$$

is lost.

If the flue-gas analysis shows that CO exists it may be important or desirable to know the amount of heat loss due to incomplete combustion.   The following formula is convenient for estimating this quantity.

$$L' = 10,150 \left(\frac{CO}{CO + CO_2} \right) C$$

Where

$L' = $ B.t.u. lost per pound of fuel;

CO = Percentage by volume of carbon monoxide in the flue gas;

CO_2 = Percentage by volume of carbon dioxide in the flue gas;

C = Decimal part by weight of total carbon in the fuel.

To illustrate, assume the following: CO, 1.3 per cent.; CO_2, 15.2 per cent., and total carbon in the fuel, 72.8 per cent. The heat loss due to incomplete combustion would be, in such a case,

$$L' = 10{,}150 \left(\frac{1.3}{1.3 + 15.2} \right) 0.728$$

$$L' = 10{,}150 \times \frac{1.3}{16.5} \times 0.728 = 582.27 \; B.t.u. \; per \; lb.$$

CHAPTER V

DRAFT AND ITS MEASUREMENT

In a natural-draft plant the chimney plays a far larger part than is commonly suspected in determining whether operating results are to be satisfactory or not. A chimney which is too small means poor draft and sluggish combustion with all its attending annoyances and losses. A chimney which is too large means waste of money in first cost and, often, loss due to excess air. Consequently, it is fitting that a few points about chimney design be taken up at this juncture.

NATURAL DRAFT

Before the actual formulas for figuring chimney sizes suitable for certain conditions are studied, it is well to get a thorough understanding of the principles of natural draft.

This old earth is entirely surrounded by an ocean of a gas mixture called air. The depth of this ocean is not known, but is estimated at all the way from 50 to 500 miles. As we transact most of our business at the bottom of this ocean we do so under a normal pressure, due to the weight of the air, of 14.7 lb. per sq. in. at sea level. As we get above sea level, naturally the pressure decreases because there is less air above pressing down.

The volume of all gases, air included, is greatly influenced by change in temperature or pressure. With increase in temperature the air expands, that is, the volume increases. With increase in pressure the volume diminishes. These changes in volume, due to changes in temperature or pressure or both, take place according to well known laws. Hence, if the volume of given weight of a gas at a given temperature and pressure is known, it is possible to figure exactly what the volume would be at some other temperature and pressure.

For every ordinary purpose we may take the atmospheric pressure (at or near sea level) as 14.7 lb. per sq. in., although actually the pressure is constantly varying slightly, due to changes in the condition of the air. As natural draft has to do with air at atmospheric pressure only, and as we have decided to consider this pressure as being fixed at 14.7 lb. per sq. in., there remains only one variable—temperature—to consider during the study of the present subject.

ABSOLUTE TEMPERATURE

With the pressure remaining the same the volume of a given weight of air increases or decreases $\dfrac{1}{492}$ of its volume at 32 deg. F. for every increase or decrease of 1 deg. in its temperature. For instance, if a pound of air at atmospheric pressure and 32 deg. F. has a volume of 12.39 cu. ft., at 100 deg. F. (the pressure remaining the same) its volume will have increased by

$$12.39 \times \frac{100 - 32}{492} = 1.71 \ cu. \ ft.$$

Hence, its volume at 100 deg. would be

$$12.39 + 1.71 = 14.1 \ cu. \ ft.$$

This law holds good for all temperatures dealt with in steam power-plant work. If it held good for all possible temperatures, that is, if a gas continued to shrink $\dfrac{1}{492}$ of its volume at 32 deg. F. for every degree drop in temperature, when the temperature dropped the 32 deg. from the freezing point to zero and then dropped 460 deg. below zero, thus dropping a total of

$$460 + 32 = 492 \ deg.$$

the gas would disappear entirely. Such low temperature has never actually been attained; hence, we do not know whether

or not a change in the law takes place, but it is quite certain that one does.

As a result of the above law governing the expansion and contraction of gases through change in temperature an imaginary standard for temperature has been invented, which is convenient to use when solving problems dealing with gas temperature and volume. Temperatures expressed according to this standard are known as absolute temperatures. The zero according to the absolute scale is 460 deg. below the zero on the Fahrenheit scale. Hence, the absolute temperature of any gas is its Fahrenheit temperature plus 460.

For instance, the absolute temperature of a gas at 92 deg. F. is

$$92 + 460 = 552 \ deg.$$

The convenient thing about these absolute temperature units is the fact that where the pressure remains the same the volume varies in direct proportion to the absolute temperature.

To illustrate, if the volume of a gas is 14 cu. ft. per lb. at one temperature, say, 60 deg., and it is desired to estimate the volume at some other temperature, say, 109 deg., the pressure being the same in each case, it is simply necessary to multiply by the ratio (expressed as a common fraction) of the two absolute temperatures. The absolute temperature corresponding to 60 deg. F. is 60 + 460 = 520 deg., and that corresponding with 109 deg. is 109 + 460 = 569 deg. Hence, the volume at 109 deg. would be

$$14 \times \frac{569}{520} = 15.31 \ cu. \ ft.$$

The following simple formula gives the pressure, volume or temperature of one pound of air when any two of these factors are known

$$Pv = 53.37 \ T$$

where

P = absolute pressure in pounds per square foot;

v = volume in cubic feet of 1 lb. of air;

T = absolute temperature of the air in degrees Fahrenheit.

Transposed to the form most convenient for calculating volume the formula is written thus

$$v = \frac{53.37}{P} T$$

To apply in a practical problem, assume it is desired to figure the volume of a pound of air at atmospheric pressure (14.7 lb. per sq. in.) and 70 deg. F.   The absolute temperature corresponding with 70 deg. F. is $70 + 460 = 530$ deg.   The pressure per square foot in the present example is $14.7 \times 144 = 2116.8$ lb. Then, substituting these values in the formula, we have

$$v = \frac{53.37 \times 530}{2116.8} = 13.36 \; cu. \, ft.$$

MEASUREMENT OF DRAFT

Draft, whether mechanical or natural, is measured by a draft gage and usually expressed in inches of water similarly to a vacuum, except the latter is expressed in inches of mercury.
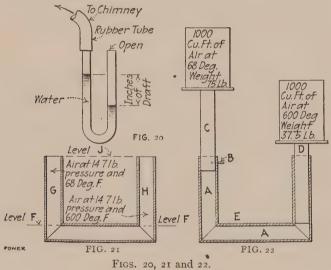
The simplest form of draft gage is a U-shaped tube of ordinary glass, as in Fig. 20, and is usually fitted with a scale in inches and decimal fractions of an inch.   One leg of the tube is connected with the furnace, flue, chimney, or other place where the draft is to be measured, and the other leg is left open to the atmosphere. The draft is the inches of difference in level between the water in the two legs as indicated in the figure.

There are numerous other forms of gage, most of which are designed to give more accurate readings for small variations in draft than the one shown, but the principle of construction and the unit of measurement are the same.

PRINCIPLE OF DRAFT

Probably every reader understands the underlying principle of natural draft in a general way, but some may be a little confused as to how the height of chimney and temperature of gases affect

intensity of draft. So, to make this basic theory quite evident to all, a little space will be given it at this point.

Imagine a pair of frictionless and sensitive plunger scales, as in Fig. 22, located in an absolute vacuum. The connecting tube A is filled with some frictionless and weightless fluid.   Next, imagine that 1000 cu. ft. of air at some ordinary atmospheric pressure and temperature, say, 14.7 lb. per sq. in. and 68 deg. F., were wrapped up in a bundle and placed on the platform of one plunger and 1000 cu. ft. of air at the same pressure but at a tem-

FIGS. 20, 21 and 22.

perature of 600 deg. F. were done into a similar bundle and placed on the other plunger platform.

The weight of the 68-deg. air would be 75 lb. while that of the 600-deg. air would be 37.5 lb. or just one-half that of the former. The cooler air being 37.5 lb. heavier than the warmer, if the pin B were withdrawn, plunger C would tend to sink and plunger D to rise, due to the 37.5 lb. difference.

Now, assume that the plungers C and D are removed, as in

Fig. 21, and that leg G is filled down to the level F with 1000 cu. ft. of air at 14.7 lb. pressure and 68 deg. F. and leg H to the same level with air at the same pressure but at a temperature of 600 deg., the top of both legs being open.

If each leg is 100 ft. high above level F, the inside area of each must be 10 sq. ft. or 1440 sq. in., and the pressure per square inch at level F in leg G, due to the weight of air in the leg, must be 75 (weight of 1000 cu. ft. of air at 14.7 lb. pressure and 68 deg.), divided by 1440; which equals 0.052 lb. per sq. in.*

Similarly, the pressure at F in tube H, due to the weight of the air at 600 deg., must be

$$37.5 \div 1440 = 0.026 \; lb. \; per \; sq. \; in.$$

Thus, there is a difference in pressure in the two legs at level F of

$$0.052 - 0.026 = 0.026 \; lb. \; per \; sq. \; in.$$

with a consequent tendency of the air in leg G to flow into leg H and push out the lighter air in the latter.

Now, if the vacuum be destroyed and the tube be submitted to the ordinary atmospheric pressure (say, 14.7 lb. per sq. in. at level J) the tendency of the cold air in leg G to force out the hot air in H will be just as strong as it was in the vacuum. This is true because the pressure at level F in leg G is 14.7 lb. per sq. in. (the atmospheric pressure at level J) plus the weight of the air contained in the leg, divided by the square inches of area of the tube, thus

$$14.7 + \frac{75}{1440} = 14.752 \; lb. \; per \; sq. \; in.$$

* This method of calculating the pressure due to the weight of a fluid is used simply to make the description more clear. If the legs were not absolutely uniform in sectional area throughout their height this method would cause error. It should be remembered that the pressure due to the weight of a liquid or a gas depends only upon the vertical depth from the surface of the fluid to the point under consideration and the weight of a unit volume of the fluid. The size and shape of the containing vessel have nothing to do with the pressure.

Similarly, the pressure at level F in tube H is

$$14.7 + \frac{37.5}{1440} = 14.726 \; lb. \; per \; sq. \; in.$$

Hence, the tendency of the cold air in G to push out the hot air in H is the same as under the former conditions, the difference in pressure being the same

$$14.752 - 14.726 = 0.026 \; lb. \; per \; sq. \; in.$$

Now, as the pressure and temperature of the air outside the tube are identical with those of the air within leg G, this leg performs no useful function and may be dispensed with, when we have left a natural-draft chimney.

Thus, we see that natural draft is due to a difference in pressure due to a difference in weight between two columns of gas of equal height. And as the outside pressure (the atmospheric pressure) acting on these two columns is equal for any given height, this difference in weight depends upon the difference in temperature. As the pressure due to the weight of a column of fluid depends only upon the height of the column and the weight of a unit volume of fluid, and not upon the cross-sectional area nor the shape of the column, the intensity of draft is proportional to the height of the chimney above the fire.

To sum up, then, the intensity of draft depends upon the height of the chimney and the difference in temperature between the outside and the stack gases.

The following formula may be used to estimate the intensity of draft to be expected from a chimney under given conditions.

$$D = 0.52 \, H \times P \left(\frac{1}{T} - \frac{1}{T'} \right)$$

where

D = draft in inches of water;

H = height of chimney above grates in feet;

P = atmospheric pressure in pounds per square inch;

T = absolute temperature of the outside air in degrees;

T' = absolute temperature of chimney gases in degrees.

Thus, with a chimney 175 ft. high above the grates in which the gases are rising at a temperature of 560 deg. F. when the outside air is at 60 deg. and the atmospheric pressure at 14.7 lb. per sq. in., the draft would be

$$D = 0.52 \times 175 \times 14.7 \left(\frac{1}{520} - \frac{1}{1020} \right)$$

$$D = 0.52 \times 175 \times 14.7 \times 0.00094 = 1.26 \ in.$$

CHAPTER VI

CHIMNEY DESIGN

When water is conveyed in a pipe the quantity delivered per unit of time depends upon the diameter and length of the pipe, the friction due to the nature of the pipe surface and the kind and number of the turns in the pipe, the difference between the pressure or head at the starting point and at the delivery point.

For illustration, consider a 1-in. pipe line, 300 ft. long, arranged as shown in Fig. 23. Assume that under the conditions shown, 9 gal. of water is delivered per minute and that it is desired to increase the quantity to, say, 12 gal. per min. As the nature of the pipe surface and the number of turns cannot be changed, it will be necessary to increase the head H or increase the diameter of the pipe to secure the desired result.

The increase in head would have to be considerable, something like 200 ft., while the necessary increase in diameter would be but slight. But, if it were required to deliver the original quantity of water against a resistance or back pressure due to, say, a partial obstruction at the end E, or at any other place, increasing the diameter of the pipe would be of but slight use. The only benefit derived would be a certain reduction in the friction of the pipe itself, which would leave just that much more pressure available at E for overcoming the resistance there, resulting in a somewhat increased flow.

On the other hand, any increase in head H, produced by raising the upper tank, would almost all be available for overcoming the local resistance or back pressure at E, the only amount lost being due to the slight additional friction of the required additional length of vertical pipe.

The principles of boiler-furnace draft, produced by a chimney, are very similar to those involved in the foregoing illustration. One difference in actual application is that the chimney system

seemingly works upside down. The boiler room itself corresponds to the overhead tank in Fig. 23; the furnace, gas passages of the boiler, breeching and chimney are the piping system. But, instead of the flow being downward, as in the case of the water system, it is upward. Nevertheless, gravity is the actuating force in both cases. The heavy cool air outside the chimney containing the light, hot gases has, due to the force of gravity, a continual tendency to seek its own levels in the chimney and force up the light gases. It never succeeds, however, for as long as the fire is maintained the heavy cool air is converted into light hot gas in passing through the fuel bed.

The important point of comparison between the water system here illustrated and a natural-draft

FIG. 23.—Illustration to show principal of chimney draft.

system is that similar changes in dimensions or design produce similar results. If it is desired to increase the head (or draft) so that a certain rate of flow may be maintained against a given resistance, logically, the height of the water pipe or chimney, as the case may be, must be increased. While increasing the area of the piping or the gas passages helps to a slight extent, the main resistance (at E, Fig. 23, or at the fuel bed in the case of a draft problem) is usually so large that only a change in height will suffice. In other words, the head or draft, or tendency to flow—whichever you call it—must be great enough so that the resistance or friction will be overcome and there will still remain a certain amount of draft to produce a flow or velocity sufficient to handle the required quantity of gas per unit of time.

When this condition has been fulfilled the size of breeching
and diameter of chimney must be determined. Here, just as
with the water piping, the area of the passages is the factor which
has the greatest effect on the capacity (volume of gas handled per
unit of time). And it is poor economy to add to the height simply
to increase the capacity by making the velocity abnormally high.

Estimating Draft Required

Before we are in a position to design a suitable chimney for
a given plant we must have some data as to the draft that will
be required under the working conditions. Knowing this, we
can then determine the necessary height. To estimate the
draft that will be required we must know the approximate nature
of the fuel to be burned, the rate at which the fuel is to be burned,
the grate area, the type of boiler to be used, manner of baffling,
length of the breeching, its cross-sectional area and the number
of turns it makes. In fact, we should know, if possible, all the
factors that affect the draft and the amount of their influence.

Unfortunately, it is almost impossible to permanently deter-
mine all the factors. After a plant has been running a year or so,
it may be necessary to change the grade of coal used. Or, it
may be necessary to add more boilers than were originally pro-
vided for or to greatly overload the existing plant. All these
changes would have their effect on the draft requirements.
Hence, as the load on the stack is usually increased and but seldom
diminished, it is a good and safe mistake to make the chimney
too large rather than too small. The intelligent engineer will
offset too much stack capacity by a careful use of the dampers,
but he is helpless if he is afflicted with a heavily overloaded
chimney.

The study of draft losses in a boiler installation is such a
broad one and so many factors enter into the problems involved
that it is impossible to do more than briefly outline the details
here.

In calculating the draft required for a given installation allow
0.001 in. of water for each foot in the length of the breeching,

measured from the chimney to the nearest boiler; 0.05 in. for each right-angle turn in the breeching, and 0.4 in. for the boiler or boilers, themselves.

These figures are based on average conditions and they are safe for use with most of the ordinary installations where the cross-sectional area of the breeching is 20 per cent. greater than the smallest free cross-sectional area of the chimney and where the boiler is of any standard design and has the usual baffle and gas-passage arrangements.

After having allowed a certain quantity of draft for overcoming the resistance of the boilers and gas passages it is next necessary to estimate the draft required at the fuel bed. This factor depends on the kind and size of the fuel to be burned and the rate of combustion required to carry the load on the boiler.

To estimate the rate of combustion it is necessary to take into consideration the maximum horsepower to be developed; the pounds of coal required to develop one horsepower-hour, and the area of the grade. Multiplying the first two factors together and dividing by the last gives the rate of combustion in pounds per square foot of grate per hour. When this quantity has been estimated the approximate draft required may be obtained from Table 2, compiled from some data given in "Stirling" and some furnished by the Green Engineering Co.

TABLE 2.—DRAFT REQUIRED IN INCHES OF WATER FOR VARIOUS COALS AND RATES OF COMBUSTION

Kind of Coal	Pounds of Coal Burned per Sq. Ft. of Grate per Hr.								
	10	15	20	25	30	35	40	45	50
Run-of-mine—bituminous	0.07	0.12	0.18	0.23	0.30	0.37	0.45	0.52	0.60
Bituminous slack	0.09	0.14	0.23	0.30	0.40	0.48	0.57	0.65	0.75
Run-of-mine—semi-bituminous	0.07	0.14	0.23	0.32	0.45	0.60	0.77	0.95	1.20
Semi-bituminous slack	0.10	0.16	0.28	0.40	0.57	0.73	0.90	1.10	1.37
Anthracite pea	0.16	0.30	0.45	0.64	0.88	1.25			
Anthracite No. 1 buckwheat	0.23	0.43	0.68	1.00	1.40				
Anthracite No. 3 buckwheat	0.39	0.75	1.25	2.00					

To illustrate, assume that it is desired to find the draft required by an installation of four 400-hp. boilers, the maximum load on which is to be 2000 hp.; the fuel is to be a fair grade of semi-bituminous mine run, $3\frac{1}{2}$ lb. of which are sufficient to develop one boiler horsepower under fair, average conditions; the area of the grate under each boiler is 88 sq. ft. The breeching is 30 ft. long and has one right-angle turn.

The draft loss for the breeching will be

$$(30 \times 0.001) + 0.05 = 0.08 \ in. \ of \ water$$

and assuming 0.4 in. for the boilers themselves, the total draft loss from furnace to stack will be

$$0.4 + 0.08 = 0.48 \ in.$$

As 2000 hp. are to be developed requiring the combustion of $3\frac{1}{2}$ lb. of coal per boiler horsepower per hour, the total coal to be burned per hour equals

$$2000 \times 3.5 = 7000 \ lb.$$

As the total grate area is

$$4 \times 88 = 352 \ sq. \ ft.,$$

the pounds of coal burned per square foot of grate per hour will be

$$\frac{7000}{352} = 19.9$$

By referring to Table 2 it will be found that 0.23 in. of draft is required for the combustion of run-of-mine semi-bituminous coal at a rate of approximately 20 lb. per sq. ft. of grate per hour. Then, adding this quantity to the quantity estimated to be required to overcome the resistance of the boiler and breeching, we have a total draft requirement of

$$0.48 + 0.23 = 0.71 \ in. \ of \ water.$$

The next step is to estimate the height of chimney required to develop this amount or intensity of draft.

Height of Chimney

In a previous chapter a formula was given for estimating the amount of draft to be expected of a chimney of a given height under certain conditions. By rearranging and modifying this formula slightly it will serve for estimating the height of chimney required when the draft is known. The original form was

$$D = 0.52\, H \times P\,\left(\frac{1}{T} - \frac{1}{T'}\right)$$

By transposing the factor H to the left side of the equation the formula takes a more convenient form for its present application, thus,

$$H = \frac{D}{0.52\, P\,\left(\frac{1}{T} - \frac{1}{T'}\right)}$$

where D represents the draft required and all the other symbols are the same as in the previous case.

Now, the chimney itself offers some resistance to the flow of the gases and allowance should be made for this. A common estimate of this loss is 20 per cent. of the total draft developed. That is, if a perfectly frictionless imaginary chimney could develop, say, 1.25 in. of draft, in actual practice a chimney of the same size would develop only 80 per cent. of this figure, or 1 in., the other 20 per cent. being lost in overcoming the friction that every actual chimney possesses.

Hence, in applying the foregoing formula we should first increase by 25 per cent. the figure representing the draft required, so as to obtain a chimney of such height that 20 per cent. of the estimated draft may be lost and still leave the required amount.

Or, better still, we can change the formula to take care of this by multiplying the draft required by the factor 1.25, making the formula read thus:

$$H = \frac{1.25\,D}{0.52\,P\left(\dfrac{1}{T} - \dfrac{1}{T'}\right)}$$

In applying this formula to the draft problem just illustrated, we must first ascertain what the average atmospheric pressure (P) is at the location of the plant. At or near sea level, this pressure may be taken as 14.7 lb. per sq. in., but where the altitude is considerable, as, for instance, at Denver, which is at an elevation of over 5000 ft. above the sea, a closer figure should be taken. At Denver, 12.5 lb. per sq. in. would be proper.

We must also ascertain what the average atmospheric temperature is at the place where the plant is located and estimate what the temperature of the flue gases probably will be. The last-mentioned factor will depend upon the design of the boiler, arrangement of baffles, cleanliness of the heat-absorbing surfaces, rate of combustion, and, somewhat, upon the efficiency of combustion. On an average the flue-gas temperature ranges between 450 and 600 deg.

In our present example, assume that the atmospheric pressure is 14.7 lb. per sq. in., the atmospheric temperature is 70 deg. F., and the temperature of the flue gases 500 deg. F. The corresponding absolute temperatures are 530 and 960 deg., respectively.

Substituting in the formula, then, we find the height of chimney required to develop an available draft of 0.71 in. is

$$H = \frac{1.25 \times 0.71}{0.52 \times 14.7\left(\dfrac{1}{530} - \dfrac{1}{960}\right)} = \frac{0.8875}{7.644\left(\dfrac{430}{508,800}\right)}$$

$$= 137.38\,ft.$$

or, in round numbers, 140 ft. above the grates.

DIAMETER OF CHIMNEY

Having determined the proper height of chimney for a given set of conditions it is next necessary to estimate the required free cross-sectional area. For this the following formula may be used:

$$E = \frac{F}{16.65 \sqrt{H}}$$

where

E = cross-sectional area of the chimney in square feet;
F = pounds of fuel to be burned per hour;
H = height of chimney above the grates in feet.

Applying this formula to our example, we have

$$E = \frac{7000}{16.65 \sqrt{140}} = \frac{7000}{16.65 \times 11.83} = 35.5 \; sq. \, ft.$$

The diameter of a chimney of this area would be about 6 ft. 9 in.

Chimneys are usually built circular because this form is cheaper, more stable and more efficient than any other. It is cheaper because less material is required for a chimney of a given cross-sectional area; more stable because the curved surface of a round chimney offers less resistance to the wind than the flat surface of a square or other polygonal (many-sided) chimney; also, because structurally the circular section is stronger. A circular chimney is more efficient because the resistance to the flow of the gases is less per unit of sectional area and the amount of exposed surface is less than with any other shape due to the fact that the circumference of a circle is shorter than the perimeter of a square or polygon.

PRACTICE PROBLEM

By way of exercise, those who are interested may work out the dimensions of a chimney for the following conditions: Eight 500-hp. boilers, with grates 83 sq. ft. in area, to be fired with bituminous slack, the combustion of 4 lb. of which is required

per boiler horsepower-hour. At times the boilers will be over-
loaded 25 per cent. The breeching is 50 ft. long from the chimney
to the nearest boiler and has two right-angle turns in it. The
plant is located about 2000 ft. above sea level, where the average
atmospheric pressure is 13.57 lb. per sq. in. The temperature
of the outside air will average 60 deg. F. and that of the flue
gases 550.

Solution of Chimney Problem

The draft required for the breeching is,

$$(50 \times 0.001) + (2 \times 0.05) = 0.15 \ in.$$

which, added to the draft required by the boilers, makes a total of

$$0.15 + 0.4 = 0.55 \ in.$$

for breeching and boilers. The rated boiler horsepower of the
installation is

$$8 \times 500 = 4000$$

and as this will be subject to a 25 per cent. overload we must
provide a chimney for

$$4000 \times 1.25 = 5000 \ hp.$$

As it is estimated that 4 lb. of coal will be required to develop one
boiler horsepower, the total maximum consumption will be

$$5000 \times 4 = 20,000 \ lb. \ per \ hr.$$

The total grate area is

$$83 \times 8 = 664 \ sq. \ ft.$$

Hence, the pounds of coal burned per square foot of grate per
hour are

$$20,000 \div 664 = 30.12$$

And the draft required for the combustion of bituminous slack at the rate of 30 lb. per sq. ft. of grate per hour is, according to the table given on page 97, 0.4 in. of water. Then, the total available draft necessary is

$$0.55 + 0.4 = 0.95$$

Applying this figure in the formula for estimating the height of chimney we have

$$H = \frac{1.25 \times 0.95}{0.52 \times 13.57 \left(\dfrac{1}{520} - \dfrac{1}{1010}\right)} = 180.47 \ ft.$$

as the required height of chimney above the grates.

Employing the formula for figuring the necessary cross-sectional area of the chimney we have

$$E = \frac{20,000}{16.65\sqrt{180.47}} = 89.44 \ sq. \ ft.$$

which would mean a chimney 10 ft. 8 in. in diameter.

CHAPTER VII

EVAPORATION

WATER

Water is composed of the two gases, hydrogen and oxygen combined chemically in the proportion by volume of two parts of hydrogen and one part of oxygen. The chemical formula is H_2O, which should be familiar to all who have followed this series from the start, as water is the product formed by the combustion of the hydrogen found in such fuels as coal, oil, gas, etc. The reaction which takes place was explained in the first lesson on combustion, pages 1 and 2.

Water in the liquid state and at 62 deg. F. weighs 62.355 lb. per cu. ft. Its weight or volume varies with changes in temperature. At 212 deg. F. the weight per cubic foot is 59.76 lb. and at 32 deg., 62.418 lb. Because of this difference in weight at different temperatures, circulation can be established by applying heat. The water in the bottom of a system expands or becomes lighter when heated and rises or is forced up by the heavier cold water above, which flows down and takes its place and in turn is heated and rises.

BOILING TEMPERATURE

If sufficient heat is applied to water in its liquid state it will commence to boil. This boiling results in some of the water being converted into a vapor which is called steam, and if the boiling is continued all the liquid will be changed into steam. The temperature at which water will boil depends upon its purity and the pressure to which it is subjected. Pure water in an open vessel subjected to the normal atmospheric pressure at sea level of 14.7 lb. per sq. in. boils at 212 deg. F. The common impurities

found in water in its natural states tend to raise the boiling temperature. Thus, sea water which contains salt as its principal impurity will not boil under atmospheric pressure until the temperature reaches 213 deg. or a little higher, depending on the exact percentage of the impurities contained. The influence of impurities on the boiling temperature is very slight (compared with the influence of pressure), and as the water used in steam boilers never contains but a comparatively small quantity of impurities, this influence is customarily neglected in steam-plant work.

For every pressure there is a fixed temperature at which water boils. The higher the pressure the higher the boiling point. If the temperature of boiling water or of the steam being formed therefrom is known, the pressure can be ascertained without a gage, simply by referring to a table of temperatures and pressures, as these always correspond. In a like manner, if the pressure is known the temperature can be determined without a thermometer.

The same principles apply when water freezes to form ice. Pure water at the normal atmospheric pressure at sea level (14.7 lb. per sq. in.) freezes at 32 deg. F. Impurities tend to lower the freezing point. Thus, ordinary sea water freezes at about 27 deg. The higher the pressure the lower the freezing point.

When water is undergoing the process of boiling the steam formed has the same pressure and temperature as the boiling water from which it is being formed or evaporated. Such steam is known as saturated steam.

Now, if heat is applied to the steam itself and the containing apparatus is arranged in such a manner that the steam is not in close contact with water and hence cannot impart this extra heat to the water to form more steam, the temperature and pressure will both tend to rise. But the new temperature of the steam will not correspond with the boiling temperature of water at a pressure equal to the new pressure of the steam. The temperature will be higher. Such steam is called superheated steam.

To sum up, then, the boiling point of water depends upon the pressure; the boiling temperature is fixed and unchangeable for any given pressure. Saturated steam is steam that has the same temperature as boiling water under equal pressure. Superheated steam is steam that has a higher temperature than boiling water under the same pressure.

Saturated steam may be dry or wet. Dry saturated steam is steam that has been thoroughly evaporated and does not carry any drops, globules, or particles whatsoever of liquid water in the form of a spray or mist. A clearer and more definite explanation of the difference between dry and wet steam will be given later.

EVAPORATION

Ebullition is the name sometimes given to the process of boiling or steam generation; a commoner name is evaporation. We speak of the evaporation per pound of coal, equivalent evaporation, etc. Then, there is another term often used: vaporization, the process of changing from a liquid to a vapor, that is, of changing from liquid water to steam. Although the last two terms really mean the same thing, custom has established a slight distinction. Evaporation has come to mean the whole process of making steam, starting with the warming up of the feed water to the boiling temperature and including the actual conversion of the water into steam, while vaporization has come to be considered simply the actual conversion from water at the boiling point into steam at the same temperature and pressure.

LATENT HEAT

When we apply heat to a body we instinctively think of an accompanying rise in temperature. For instance, if we apply heat to a piece of iron we know that the temperature of the iron quickly goes up. When we apply heat to water, say, at 60 deg., the water grows warmer—its temperature rises. The water will continue to get hotter, the more heat we add, until the boiling point is reached. If the water is in an open vessel and at sea

level this point will be at the 212 deg. mark. Now, right here a strange thing will occur. The water will fail to get any hotter. No matter how much heat we apply, no matter how hard we force the fire or how high we turn the gas burner, whichever it happens to be, the thermometer will stick at 212 deg. If you doubt this, try the experiment with a pan of water and thermometer and convince yourself.

The water will cease getting hotter, but at the same time something else will happen. The instant the boiling point is reached ebullition—the process of steam generation—will set in. The question naturally arises: If the temperature cannot be increased by applying more heat, what becomes of this extra heat? It is used in converting the liquid water into steam. As soon as the heat is shut off the boiling or steam-making will cease, proving that heat is required to convert the water from the liquid into the vaporous state. The more heat we apply the more rapid will be the rate of steam generation.

It requires 970.4 B.t.u. to change 1 lb. of water at atmospheric pressure and a temperature of 212 deg. into steam at the same temperature. Just why so much heat is used up or absorbed without causing a rise in temperature when water is broken up into steam I will not attempt to explain here. The only really important thing to know is that such is the case. The heat thus absorbed is called latent heat of vaporization or the latent heat of steam. The term latent means hidden or secret. Hence, the latent heat of steam is the heat that is taken up and hidden by the water when it changes from its liquid to its vaporous state. We consider the heat as being latent or hidden because we can see no evidence of its having gone into the steam as far as the thermometer can tell us.

When steam condenses the heat transfer is the other way. If a pound of steam at atmospheric pressure were injected into a tank containing 99 lb. of water at, say, 60 deg., so that all the steam condensed back into water, the temperature of the resulting 100 lb. of water would be 71.2 deg., showing a rise of 11.2 deg. for the original 99 lb. of water.

The temperature of steam at atmospheric pressure is 212 deg. Hence, the drop in temperature was only

$$212 - 71.2 = 140.8 \ deg.$$

But the 99 lb. of water rose 11.2 deg., showing that

$$99 \times 11.2 = 1108.8 \ B.t.u.$$

were imparted to it. (One B.t.u. being the amount of heat required to raise the temperature of 1 lb. of water 1 deg.)

If the steam had been condensed before it was injected into the 99 lb. of water so that it went in as a liquid at 212 deg. instead of a vapor at 212 deg., the rise in temperature of the 99 lb. would be only 1.52 deg. because the pound of condensed steam or water at 212 had only

$$212 - 60 = 152 \ B.t.u.$$

more in it than a pound of the cooler water.

Some, who are just beginning the study of evaporation and steam, may experience a little difficulty in realizing that steam has weight, and, hence, may be slightly confused when they come in contact with such terms as pounds of steam, etc. This confusion is all the more likely because the pressure is also spoken of in terms of pounds.

In an earlier lesson (page 7) it was shown that a gas has weight, and in the same manner it could easily be demonstrated that steam has weight. In fact, the weight of steam can be ascertained more easily than the weight of a gas; all that is necessary is to condense the steam and weigh the resulting water. In referring to a quantity or weight of steam the word "of" is employed. Thus, we say, 9 lb. *of* steam evaporated per pound of coal. Which means that the combustion of a pound of coal has caused the evaporation of 9 lb. of water, resulting in the generation of 9 lb. of steam.

In referring to pressure we use the word "at." Thus, steam *at* 150 lb. Which means steam which causes or possesses a pressure of 150 lb. on each square inch of the surface confining it.

STEAM TABLES

The boiling temperature of water is different for different pressures. Thus, at atmospheric pressure (14.7 lb. per sq. in. absolute, or zero gage) the boiling temperature is 212 deg. F., while at 150-lb. gage it is 365.9 deg. The higher the pressure, the higher the boiling temperature.

In addition, the latent heat, or the quantity of heat required to convert a pound of the water from its liquid to vaporous form, varies quite extensively with variation in pressure. Thus, the latent heat of steam at atmospheric pressure is 970.4 B.t.u. per pound, while at 150-lb. gage it is only 856.9 B.t.u., or more than 100 B.t.u. less per pound. The higher the pressure, the lower the latent heat.

The volume of a pound of steam varies greatly with variation in pressure. At atmospheric pressure 1 lb. of steam has a volume of 26.79 cu. ft., while at 150-lb. gage the volume is only 2.758 cu. ft., or only about one-tenth as much. The higher the pressure the smaller the volume per unit of weight. It is this characteristic of the steam that makes it suitable for use in engines, turbines, etc. The steam is generated at a high pressure with a small volume per unit of weight, then let into the cylinder or turbine stage where its pressure forces the piston ahead—provided the resistance of the piston is not greater than the pressure of the steam, which is the case when the engine is on dead center or when it is too heavily loaded.

As the pressure of the steam forces the piston forward, more room is created in the cylinder and the pressure is slightly relieved or lowered. As the pressure lowers, the steam must expand to fill the increased space because for every pressure there is a corresponding volume just the same as for every pressure there is a corresponding boiling temperature, latent heat, etc. And the relation of these quantities to each other never varies so long as steam is steam. They must fulfill Nature's laws, which are immutable—cannot be repealed or changed.

However, this action of steam in the cylinder of an engine

is a little off the subject now occupying our attention, and a more thorough study of it will be offered in its proper turn later on.

Because the boiling temperature, latent heat, etc., are different for each different pressure, we have what are called the steam tables, or, to be more exact, tables of the properties of saturated steam. These are exceedingly convenient for finding the other factors when any one is known, and it behooves all who intend to continue on in power-plant study and work to become familiar with the tables.

A modified and condensed form of the latest accepted steam tables is presented herewith. The original tables were compiled by Professors Lionel S. Marks and Harvey N. Davis, and published by Longman, Green & Co., through whose courtesy we are permitted to publish Table 3, herewith.

Gage and Absolute Pressure

In the first column of the table are given the vacuum and gage pressures; in the second, absolute pressures. In the first paragraph of this lesson you may have noticed that atmospheric pressure was given as 14.7 lb. per sq. in., absolute, or zero gage. This was done because in these modern days there are, unfortunately, two standards of pressure measurement. Gage pressure takes its name from the instrument commonly used for measuring boiler steam pressure. Now, the ordinary pressure gage used on a boiler does not indicate the total pressure actually existing inside the boiler. It only measures the difference between the pressure of the steam within the boiler and the pressure of the atmosphere without.

This is due to the construction of the gage, which consists principally of a curved hollow metal tube open at one end. The hollow interior of the tube connects at the open end with the interior of the boiler while the exterior of the tube is exposed to the pressure of the atmosphere. When the pressure acting on the inside of the tube is equal to the atmospheric pressure acting on

the outside, the tube is in its normal position and the pointer on the dial of the gage, connected to the tube at the closed end, indicates zero on the scale. When the pressure within exceeds the atmospheric pressure without, the tube tends to lose its curve and straighten out. And as the closed end, to which the pointer is attached, is the only end free to move, the change in the position of the tube is all transmitted, through suitable mechanism, to the pointer. This swings away from the zero mark and points to the position on the scale corresponding with the pressure existing in the boiler over and above that of the atmosphere outside.

Absolute pressure means the total pressure actually existing in the space where the measurement is taken whether this be in a boiler, a condenser, in the open atmosphere or anywhere else. It does not take into account any outside pressure that may happen to be acting on the measuring gage or instrument. Hence, the zero point on the absolute-pressure scale is at absolute vacuum. If a whole boiler, pressure gage and all, were inclosed in a vacuum, the gage would then show absolute pressures because, there being absolutely no pressure outside, the difference between the inside and outside pressures would equal the total pressure actually existing inside the boiler.

The absolute-pressure system of measurement is the more accurate one because it is not dependent upon the more or less variable pressure of the atmosphere. An absolute-pressure gage is more complicated and expensive, however, than the ordinary gage used in boiler work, and, hence, far less popular. So, in actual steam-plant operation gage pressures are the ones mainly encountered. But gage pressures can easily be translated into absolute pressures by adding the amount of atmospheric pressure existing at the location of the plant under consideration. Thus, at sea level, absolute pressure may be taken as gage pressure plus 14.7 lb. per square inch. At a higher altitude than sea level, the atmosphric pressure is less; hence, care must be used, in cases where the difference is appreciable, that the proper value be employed. For instance, at Denver the average atmospheric

TABLE 3.—PROPERTIES OF SATURATED STEAM

From Marks & Davis' Tables.   Courtesy of Longmans, Green & Co.

1 Vacuum, in. of mercury	2 Absolute pressure, lb. per sq. in.	3 Tempera- ture, degrees Fahr.	4 Heat of the liquid h B.t.u.	5 In the steam H B.t.u.	6 Latent heat $L = H - h$ B.t.u.	7 Volume cu. ft. in 1 lb. of steam	8 Weight of 1 cu. ft. of steam, lb.
				Total heat above 32° F.			
27.88	1	101.83	69.8	1104.4	1034.6	333.0	0.00300
25.85	2	126.15	94.0	1115.0	1021.0	173.5	0.00576
23.81	3	141.52	109.4	1121.6	1012.3	118.5	0.00845
21.78	4	153.01	120.9	1126.5	1005.7	90.5	0.01107
19.74	5	162.28	130.1	1130.5	1000.3	73.33	0.01364
17.70	6	170.06	137.9	1133.7	995.8	61.89	0.01616
15.67	7	176.85	144.7	1136.5	991.8	53.56	0.01867
13.63	8	182.86	150.8	1139.0	988.2	47.27	0.02115
11.60	9	188.27	156.2	1141.1	985.0	42.36	0.02361
9.56	10	193.22	161.1	1143.1	982.0	38.38	0.02606
7.52	11	197.75	165.7	1144.9	979.2	35.10	0.02849
5.49	12	201.96	169.9	1146.5	976.6	32.36	0.03090
3.45	13	205.87	173.8	1148.0	974.2	30.03	0.03330
1.42	14	209.55	177.5	1149.4	971.9	28.02	0.03569
Lb. gage press							
0	14.7	212.0	180.0	1150.4	970.4	26.79	0.03732
5.3	20	228.0	196.1	1156.2	960.0	20.08	0.04980
10.3	25	240.1	208.4	1160.4	952.0	16.30	0.0614
15.3	30	250.3	218.8	1163.9	945.1	13.74	0.0728
20.3	35	259.3	227.9	1166.8	938.9	11.89	0.0841
25.3	40	267.3	236.1	1169.4	933.3	10.49	0.0953
30.3	45	274.5	243.4	1171.6	928.2	9.39	0.1065
35.3	50	281.0	250.1	1173.6	923.5	8.51	0.1175
40.3	55	287.1	256.3	1175.4	919.0	7.78	0.1285
45.3	60	292.7	262.1	1177.0	914.9	7.17	0.1394
50.3	65	298.0	267.5	1178.5	911.0	6.65	0.1503
55.3	70	302.9	272.6	1179.8	907.2	6.20	0.1612
60.3	75	307.6	277.4	1181.1	903.7	5.81	0.1721
65.3	80	312.0	282.0	1182.3	900.3	5.47	0.1829
70.3	85	316.3	286.3	1183.4	897.1	5.16	0.1937
75.3	90	320.3	290.5	1184.4	893.9	4.89	0.2044
80.3	95	324.1	294.5	1185.4	890.9	4.65	0.2151
85.3	100	327.8	298.3	1186.3	888.0	4.429	0.2258

TABLE 3.—PROPERTIES OF SATURATED STEAM.—*Continued*

1 Vacuum in. of mercury	2 Absolute pressure, lb. per sq. in.	3 Tempera- ture, degrees Fahr.	4 Heat of the liquid h B.t.u.	5 In the steam H B.t.u.	6 Latent heat $L = H - h$ B.t.u.	7 Volumne cu. ft. in 1 lb. of steam	8 Weight of 1 cu. ft. of steam, lb.
Lb. gage press							
90.3	105	331.4	302.0	1187.2	885.2	4.230	0.2365
95.3	110	334.8	305.5	1188.0	882.5	4.047	0.2472
100.3	115	338.1	309.0	1188.8	879.8	3.880	0.2577
105.3	120	341.3	312.3	1189.6	877.2	3.726	0.2683
110.3	125	344.4	315.5	1190.3	874.7	3.583	0.2791
115.3	130	347.4	318.6	1191.0	872.3	3.452	0.2897
120.3	135	350.3	321.7	1191.6	869.9	3.331	0.3002
125.3	140	353.1	324.6	1192.2	867.6	3.219	0.3107
130.3	145	355.8	327.4	1192.8	865.4	3.112	0.3213
135.3	150	358.5	330.2	1193.4	863.2	3.012	0.3320
140.3	155	361.0	332.9	1194.0	861.0	2.920	0.3425
145.3	160	363.6	335.6	1194.5	858.8	2.834	0.3529
150.3	165	366.0	338.2	1195.0	856.8	2.753	0.3633
155.3	170	368.5	340.7	1195.4	854.7	2.675	0.3738
160.3	175	370.8	343.2	1195.9	852.7	2.602	0.3843
165.3	180	373.1	345.6	1196.4	850.8	2.533	0.3948
175.3	190	377.6	350.4	1197.3	846.9	2.406	0.4157
185.3	200	381.9	354.9	1198.1	843.2	2.290	0.437
195.3	210	386.0	359.2	1198.8	839.6	2.187	0.457
200.3	215	388.0	361.4	1199.2	837.9	2.381	0.468

pressure is but 12.5 lb. per square inch. Consequently, the first colume of Table 3 would be over 2 lb. out of the way and should not be used for accurate work. The thing to do in such cases is to translate into absolute pressures and use the second column. For most ordinary purposes, however, the errors caused are hardly important enough to warrant any large amount of extra work.

The third column of Table 3 gives the temperature of the steam at various pressures. This temperature is also the boiling temperature of water under the corresponding pressure, as was carefully explained on page 104.

Heat of the Liquid

In the fourth column is given the heat of the liquid, or, as it is sometimes called, the heat in the water. The figures in this column represent the number of B.t.u. required to raise the temperature of 1 lb. of water from 32 deg. to the boiling temperature at the pressure given. Thus, at atmospheric pressure or zero, gage, the heat of the liquid is 180 B.t.u. This can be easily checked from the knowledge gained from previous lessons. It was learned by definition that it takes 1 B.t.u. to raise the temperature of 1 lb. of water 1 deg. Then, as there are 212 − 32 = 180 deg. difference between 32 and the boiling point, it must require 180 × 1 = 180 B.t.u. to raise 1 lb. of water from 32 deg. to the boiling temperature at atmospheric pressure.

As the pressure grows higher, the heat of the liquid does not exactly correspond with the number of degrees difference between 32 and the boiling point. Thus, at 35.3-lb. gage, or 50-lb., absolute, pressure, the number of B.t.u. required to raise the temperature of 1 lb. of water from 32 deg. to the boiling point (the heat of the liquid) is 1.1 greater than the number of degrees between those two points. This is because the heat required to raise the temperature of 1 lb. of water 1 deg. increases gradually as the pressure increases above 14.7 lb. per square inch.

In the sixth column of Table 3 are given the values of latent heat of steam at the various pressures.

Total Heat in Steam

The figures in column 5 are the sums of the figures in columns 4 and 6 and they show the total heat contained in 1 lb. of steam above the temperature of 32 deg.

It may be a source of wonder to some why columns 4 and 5 are headed "Total Heat Above 32 Deg., F." The explanation is this:

Every substance, no matter what its temperature, contains some heat. We think of a piece of ice as a pretty cold chunk of

solid water and would hardly suspect, on first thought, that it could have any heat concealed about it. Yet, a pound of ice just at the freezing point (32 deg.) possesses 16 B.t.u. more than a pound at zero temperature. Ice may possess different temperatures just the same as water, steel or steam. Then, ice at zero is certainly colder than ice at 32 deg. and, *vice versa*, ice at 32 deg . must be warmer than ice at zero, and hence it must possess more heat.

In fact, no matter how cold you may make a substance, it still must possess some heat. Suppose you refrigerated a piece of ice until its temperature went down to −75 deg., in all 107 deg. below the normal freezing point of water. That would be pretty cold, wouldn't it? Yet that ice could be refrigerated still more, say, to −100 deg., showing that even at −75 deg. it hadn't yet lost all the heat it possessed.

Man has not yet discovered just what the absolutely lowest temperature is. He has succeeded in obtaining artificially some very low degrees, but he has never reached the lowest limit because his apparatus fails first.

Then, in view of the fact that we do not know at just what temperature the point of complete lack of heat exists, we must establish a "base" line to work from when we talk of or deal with quantities involving "total" heat. In dealing with steam, this base line is the freezing point of water under atmospheric pressure, or 32 deg. F. Thus, the total heat of the liquid or in the water is the heat that must be imparted to 1 lb. of water in order to raise its temperature from 32 deg. to the boiling point. And the total heat in the steam is this quantity plus the latent heat.

Column 7 gives the volume of 1 lb. of steam in cubic feet and column 8 the weight of 1 cu. ft. in pounds.

Equivalent Evaporation

By referring to Table 3 it will be noticed that the total heat in a pound of steam gradually increases as the pressure increases. Thus, at atmospheric pressure the total heat of a pound of steam

is 1150.4 B.t.u., while at 165 lb., abs., it is 1195 B.t.u. The heat required to generate steam at a pressure of 125 lb. abs., starting with feed water at 100 deg., is 1122.3 B.t.u. The proof is this: The total heat above 32 deg., as shown by the steam table is 1190.3 B.t.u. But 68 B.t.u. were already in the water because we started with the water at 100, instead of at 32 deg., and as 1 B.t.u. will raise the temperature of 1 lb. of water 1 deg., it is evident that $(100 - 32) \times 1 = 68$ B.t.u. had already been supplied.

Then, the heat required to generate a pound of steam depends upon the pressure at which the steam is to be generated and the temperature of the feed water. It seldom happens that two boiler plants are exactly alike in both of these respects and, hence, when the performance of one plant is being compared with that of another, in order to be fair, it is necessary to have a common ground for comparison. One engineer might state, "I get an actual evaporation of 10.5 lb. of water per pound of coal," meaning that for every pound of coal fired into the furnace, 10.5 lb. of water were actually evaporated into steam under the conditions existing in his plant. He might think that he was making a better showing than his neighbor, who, although using exactly the same grade of coal, was getting an actual evaporation of 10 lb. per pound of coal. Yet, when the boiler pressure and feed-water temperature in both plants are taken into consideration, it might be shown that the man in the other plant was securing better efficiency even though the quantity of water actually evaporated per pound of fuel was somewhat less.

Assume that in the first-mentioned plant the steam pressure carried was 115 lb. per sq. in., abs., and the temperature of the feed water was 200 deg., while in the second plant the pressure was 190 lb., abs., and the feed-water temperature 100 deg.

In the first plant, the heat required to generate a pound of steam was

Total Heat in the Steam Above 32 Deg.		Heat in Feed Water Above 32 Deg.		
1188.8	—	168	=	1020.8 *B.t.u.*

And in the second plant the required heat was

Total Heat in the Steam Above 32 Deg.		Heat in Feed Water Above 32 Deg.		
1197.3	—	68	=	1129.3 $B.t.u.$

In the first plant 10.5 lb. of water were actually evaporated per pound of coal. Then, of the heat liberated by the combustion of 1 lb. of coal

$$1020.8 \times 10.5 = 10{,}718 \; B.t.u.$$

were absorbed by the boiler and went toward useful work by generating steam.

In the other plant, 10 lb. of water were actually evaporated per pound of coal, yet

$$1129.3 \times 10 = 11{,}293 \; B.t.u.$$

or 575 B.t.u. more were absorbed and went toward useful work than in the first case. Consequently, as the same quality of coal was used in each case, the efficiency of the latter plant was higher than the former.

This example emphasizes the importance of having a standard method of comparison so that the performance of all plants, no matter how widely the feed-water temperature and the steam pressure may vary, can be compared with complete fairness. The method used is to calculate the number of pounds of water that could be evaporated from a feed temperature of 212 deg. into steam at the same temperature by the heat used in evaporating 1 lb. of water from the feed temperature used in the plant discussed into steam at the pressure actually employed in that plant. The ratio of the evaporation at 212 deg. to the actual is called the "factor of evaporation." And when the number of pounds of water actually evaporated is multiplied by the factor of evaporation the product is the "equivalent evaporation" or the evaporation "from and at 212 deg."

The factor of evaporation may be found by the simple formula

$$F = \frac{(H-t)+32}{970.4}$$

where

F = factor of evaporation;
H = total heat in the steam above 32 deg.;
t = temperature of the feed water.

Applying this formula to the first plant mentioned in the example just given, the factor of evaporation is found to be

$$F = \frac{(1188.8 - 200) + 32}{970.4} = 1.052$$

Multiplying together the pounds of water actually evaporated per pound of coal and the factor of evaporation, we have

$$10.5 \times 1.052 = 11.05 \; lb.,$$

the equivalent evaporation per pound of coal. This quantity is called the equivalent evaporation because the heat put into 11.05 lb. of water at 212 deg. to make steam at 212 deg. (atmospheric, or 14.7 lb., abs., pressure) is exactly the same as the heat put into the 10.5 lb. at 200 deg. to make steam at 115 lb., abs., pressure. Hence, the two quantities are equivalent from the standpoint of heat.

Boiler Horsepower

The name horsepower was originally applied to the steam engine. James Watt, who did great work in the eighteenth century developing the steam engine, rated his engines as being able to do as much work as a certain number of work horses, hence, the unit, horsepower, which has been employed ever since. When it became desirable to apply a unit to the output or capacity of a boiler, the same name was employed. Thus, a boiler which could supply steam enough to operate a 100-hp. engine was called a 100-hp. boiler. But such a standard without further qualification was very indefinite indeed. First, because various types and sizes of steam engines require widely different quantities of steam per horsepower-hour, and second, because a boiler of given dimensions may be made to generate steam at a greatly varying rate, depending on how hard the fire is forced.

Finally, an exact standard was selected and a boiler horse-power was established as the evaporation of 30 lb. of water per hour from a feed temperature of 100 deg. into steam at a pressure of 70 lb. gage, or the equivalent evaporation of 34.5 lb. of water per hour from and at 212 deg. This standard suffices to determine the output of a boiler when in operation, but it gives no means of determining the dimensions of a boiler for a given duty. In other words, a man who wished to purchase, say, a 200-hp. boiler, had no means by which he could calculate the area of the heating surface the boiler should possess and, hence, he was forced to depend upon the manufacturer's judgment. To avoid confusion and misunderstanding, it was, therefore, necessary to establish a standard for the area of heating surface necessary to develop one boiler-horsepower. At present, this standard is generally accepted as 10 sq. ft. Thus, if a man purchases a boiler of 150-hp. rating, he expects to get a unit of such dimensions as to possess 1500 sq. ft. of heating surface. Heating surface is defined as that portion of shell, tubes and other parts which is in contact with the gases of combustion on one side and the contained water on the other.

Quality of Steam

Steam from practically all boilers, unless it passes through a superheater, contains moisture, that is, minute particles of water that has not been changed from its liquid form into the true vaporous state. By innumerable experiments it has been proven far beyond any doubt that when a pound of water at a certain temperature is evaporated into steam at a certain pressure a certain definite amount of heat is required. Now, then, if we condense a pound of what we assume to be "pure" steam (that is, saturated steam) by injecting it into a known weight of cool water and then carefully compute the heat it contained from the rise in temperature of the cooling water, we might find that the steam did not contain all the head that, according to the steam table, it should. In such a case we would know that the steam contained "moisture" or was "wet."

The reason why a pound of wet steam does not contain all the heat it should is because the part that still exists as liquid water, no matter how fine or minute the particles may be, has not taken up any latent heat.

To illustrate with an actual numerical example, let us assume that we are investigating 100 lb. of wet steam that has been given off from a boiler at 125 lb., abs., pressure. According to the steam table, a pound of pure or dry saturated steam at 125 lb., abs., pressure should contain 1190.3 B.t.u. total heat above 32 deg. F., and, hence, 100 lb. should contain 119,030 B.t.u. If this 100 lb. were injected into 6000 lb. of water at 60 deg., the resultant weight of water would be 6100 lb. and the heat it should contain above 32 deg. would be the 119,030 B.t.u. before mentioned plus 6000 times the degrees difference between 32 and 60, or 168,000 B.t.u. One B.t.u. being the quantity of heat required to raise 1 lb. of water 1 deg., it is evident that

$$6000 \times (60 - 32) = 168,000 \ B.t.u.$$

would have to be put into the water in raising it from 32 to 60 deg. Thus, the total heat above 32 deg. contained in the 6100 lb. of water should be

$$119,030 + 168,000 = 287,030 \ B.t.u.$$

And, as the number of degrees in temperature above 32 deg. must be the total heat contained in the water divided by the weight of the water in pounds the new temperature after the steam has been injected should be

$$32 + (287,030 \div 6100) = 79 \ deg.$$

But, if the thermometer showed that the actual temperature was only 78.6 deg., and if there had been no radiation loss, it would be evident that there was a deficiency in the heat added to the water by the steam of

$$(79 - 78.6) \times 6100 = 2440 \ B.t.u.$$

Then, the entire 100 lb. of what we assumed was steam in actuality must have been only part steam and part liquid water.

Now, as the temperature of this liquid water carried in the steam is the same as that of the steam itself (if for no other reason than because the steam and particles of water arose together from the main body of water in the boiler), it is evident that the heat of the liquid is not deficient, the entire 100 lb. being at the boiling temperature. Consequently, the deficiency must all be due to the fact that some of the latent heat was not absorbed. This being the case, the number of pounds of water not converted into steam but simply floating in the steam in small particles (thus contributing to the weight of the mass just the same as though it all were steam) may be discovered by simply dividing the number of lacking B.t.u. by the latent heat of 1 lb. of steam at the given pressure, 125 lb., abs., thus,

$$2440 \div 874.7 = 2.8 \text{ } lb.$$

Then, of the 100 lb. of what we assumed was steam only

$$100 - 2.8 = 97.2 \text{ } lb.$$

or 97.2 per cent. really is steam. We say, consequently, that the "quality" of this steam is 97.2 per cent., or that the steam is "97.2 per cent. dry."

Practice Problems

A boiler is running under 120 lb., abs., pressure on feed water at 160 deg. What is the factor of evaporation?

If the actual total evaporation per hour is 8760 lb., what is the number of boiler horsepower being developed?

Solution of Practice Problems

The factor of evaporation for the conditions specified in the problem may be ascertained by means of the formula:

$$F = \frac{(H - t) + 32}{970.4}$$

By referring to the steam table it will be seen that the total heat of
steam at 120-lb., abs., pressure is 1189.6 B.t.u.   Then substituting
in the formula, we have

$$F = \frac{(1189.6 - 160) + 32}{970.4} = \frac{1061.6}{970.4} = 1.094$$

A boiler horsepower is equivalent to the evaporation of 34.5 lb.
of water per hour from and at 212 deg.   The equivalent evapora-
tion for any set of conditions is found by multiplying the actual
evaporation by the factor of evaporation.   Thus, the equivalent
evaporation for the conditions given in the problem is

$$8670 \times 1.094 = 9485 \text{ lb. per hr.,}$$

and, hence, the number of boiler horsepower being developed is

$$9485 \div 34.5 = 275.$$

Steam Calorimeters

It is important to know the quality or the percentage of dryness
of steam when comparing boiler or engine tests.   If this were not
known and taken into consideration the results of some tests
would be misleading.

Moisture in steam causes inefficiency and when present in
large quantities it is troublesome in the steam engine as it makes
cylinder lubrication difficult and may cause knocking.   It also
tends to cause water-hammer in the pipes.

The device used to discover the percentage of moisture in
steam is called a steam calorimeter.   It is not like the fuel calo-
rimeter which is used for estimating the heat value of fuels and
the two should not be confused.

There are three principal types of steam calorimeter.   One
is the barrel, in which the steam sample is injected into a barrel
of cool water and the increase in temperature and weight noted,
from which data the quality of the steam can be estimated.
This type is not popular, however, because very slight errors in

reading temperatures and weights cause large errors in the final results.

Another type is the separating calorimeter. In this the particles of moisture are separated from the steam by mechanical means in a manner similar to that used in an ordinary steam separator in a pipe line.

The third type is the throttling calorimeter, a form of which is illustrated on page 126. Where the percentage of moisture in the steam does not exceed 4 per cent. and where the steam pressure is 80 lb. gage or over, the throttling calorimeter is very accurate and convenient, hence, its use is preferable. When the contained moisture is greater than 4 per cent., this form of calorimeter is useless and one of the separating type must be used.

As the quality of the steam in the great majority of plants seldom falls below 96 per cent., only the throttling type of calorimeter will be taken up here. If its principle and operation are fully understood, no difficulty whatever will be experienced in mastering the principle and operation of the other types.

When steam in expanding forces the piston ahead in the cylinder of an engine it loses heat, which is spent in doing the work of making the engine turn and running the dynamo, shafting system or whatever the load-giving apparatus happens to be. On the other hand, when steam is permitted to expand from one pressure to another without resistance, as it does when flowing from a hole in a pipe or from a valve into the open air, it tends to retain all the heat it had.

To illustrate, assume that a boiler is generating steam at a pressure of 140 lb., abs., and that this steam is dry saturated. By referring to the steam table it may be ascertained that steam of that pressure has a total heat of 1192.2 B.t.u. per pound of steam. If this steam were allowed to flow through an opening directly into the atmosphere, we would find that the temperature of the steam after it emerged from the opening, and its pressure had dropped to that of the atmosphere, was 302.9 deg.—that is, if we were careful to avoid error due to radiation loss. The

temperature of saturated steam at atmospheric pressure is 212 deg. Then, this steam must be superheated

$$302.9 - 212 = 90.9 \; deg.$$

The total heat of dry saturated steam at atmospheric pressure is 1150.4 B.t.u. per pound. This superheated steam has all the heat of dry saturated steam and some more, as its higher temperature indicates. The specific heat of superheated steam varies for different pressures and temperature, but for the above case would be about 0.46. Hence, the excess heat must be

$$90.9 \times 0.46 = 41.8 \; B.t.u. \; per \; pound.$$

And this value added to the total heat of dry saturated steam at atmospheric pressure gives

$$1150.4 + 41.8 = 1192.2 \; B.t.u.$$

which is exactly the same as the heat contained in 1 lb. of the steam we started with, namely, dry saturated at 140 lb., abs., pressure.

Now, if the 140-lb. steam contained some moisture, the total heat in the mixture of steam and water would be less to begin with, and the difference between that heat and the total heat of steam at 212 deg. would not all go to superheating the steam at atmospheric pressure, but some of it would be used up in vaporizing the entrained moisture and the final temperature or degree of superheat would, therefore, be considerably lower than above shown.

For instance, suppose the quality of the steam were 98 per cent., that is, it contained 2 per cent. of moisture. The total heat of a pound of such a mixture of steam and water would be the heat of the liquid plus the latent heat of 0.98 lb. of steam, or

$$324.6 + (867.6 \times 0.98) = 1174.8.$$

Subtracting from this, the 1150.4 B.t.u., total heat in 1 lb. of dry saturated steam at atmospheric pressure, we have

$$1174.8 - 1150.4 = 24.4 \; B.t.u.$$

excess heat instead of the 41.8 we previously had. Hence, the degree of superheat would be

$$24.4 \div 0.46 = 53 \ deg.$$

showing a final temperature, consequently, of

$$212 + 53 = 265 \ deg.$$

Thus, by permitting steam to flow through an opening into the atmosphere, observing the temperature change, and using precaution against error due to radiation, we may calculate the quality or moisture content of such steam. A home-made form of the throttling calorimeter—the device used in doing this—is shown in Fig. 24. It can be made of pipe and fittings as shown. Between the flanges tightly fit a $\frac{1}{8}$-in. steel plate with a small orifice drilled through its center. This orifice should not be greater than $\frac{3}{32}$ in. in diameter; $\frac{1}{16}$ in. would be better. The thermometer wells can be obtained from any instrument supply house. The thermometers should have a range up to 400 deg., F., at the very lowest. While the calorimeter can be operated with fair success with only the lower thermometer and well, it is preferable to use both an upper and a lower; the increased reliability of results more than offsets the difference in cost.

When assembled and in place, the calorimeter should be well insulated with magnesia or other covering to eliminate radiation as much as possible and, hence, prevent error.

According to the boiler-testing code of the American Society of Mechanical Engineers, formulated in 1899, the nozzle A of the calorimeter "should be placed in the vertical steam pipe rising from the boiler * * * and should extend across the diameter of the steam pipe to within $\frac{1}{2}$ in. of the opposite side * * * none of these holes (in the nozzle) should be nearer than $\frac{1}{2}$ in. to the inner side of the steam pipe."

Before any readings are taken it is best to let steam blow through the calorimeter at full pressure for 5 or 10 min., so that the entire apparatus will be thoroughly warmed up and error avoided. The

thermometers should be tested for accuracy before used and if an
important variation is found allowance should be made in the
readings.   For very accurate work corrections are made for the
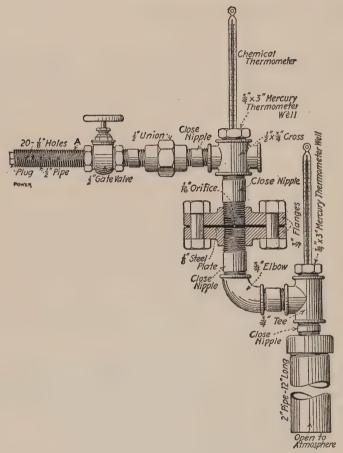
FIG. 24.—Construction of home-made steam calorimeter.

error caused by the exposure of part of the thermometer stem to
the room temperature.   But, such connections are far too small

to be of real importance in every-day power-plant test work. So, they will not be considered here.

When making a test for the quality of steam have the valve of the calorimeter wide open and read both thermometers. The temperature shown by the upper thermometer should correspond very closely with the temperature of steam at the pressure being carried on the boiler. This temperature is given in the steam table. If an appreciable difference is found this may be taken as an evidence that either the steam-pressure gage on the boiler or the thermometer is inaccurate and both should be tested to locate the trouble.

After the readings have been taken, the quality of the steam may be estimated by the following formula, which appears more formidable than it really is.

$$Q = \frac{(H - h) + 0.46\,(T - T_1)}{L}$$

where

Q = Quality of steam expressed as a decimal fraction;

H = Total heat of dry saturated steam at atmospheric pressure, B.t.u. per lb.;

h = Heat of the liquid corresponding with the pressure carried on the boiler, B.t.u. per lb.;

T = Temperature as shown by the lower thermometer, degrees F.;

T_1 = Temperature of saturated steam at atmospheric pressure, degrees F.;

L = Latent heat of steam at the pressure carried on the boiler, B.t.u. per lb.

To illustrate the use of this formula, assume that the boiler being tested is at sea level and that the temperature shown by the upper thermometer is 366 deg. and by the lower one, 266 deg.

Referring to the steam table, we would find that the steam; pressure corresponding with the temperature of 366 deg. is 165 lb., abs. If this figure checks up reasonably close with the pressure as shown by the gage on the boilers, we may proceed with

our calculating. In making the comparison, don't forget to subtract the atmospheric pressure from the figure showing the absolute pressure, in the present case, 14.7 lb.

All the factors, except Q and T, are given in the steam table; T, given by the lower thermometer of the calorimeter, is 266; Q will be the answer. Substituting,

$$Q = \frac{(1150.4 - 338.2) + 0.46\,(266 - 212)}{856.8} = \frac{837.04}{856.8}$$
$$= 0.977$$

That is, the quality of the steam is 97.7 per cent.

PRACTICE PROBLEM

At a plant considerably above sea level, the atmospheric pressure is 13 lb. per sq. in. A boiler was being tested for the quality of the steam generated. The upper thermometer of the throttling calorimeter used showed a temperature 377.6 deg., while the lower thermometer showed 286 deg. The steam-pressure gage on the boiler indicated a pressure of 177 lb., gage. What was the quality of the steam?

BOILER EFFICIENCY

SOLUTION OF PRACTICE PROBLEM

At the plant in question the atmospheric pressure is 13 lb. per sq. in. and according to the steam table, the total heat of dry saturated steam at that pressure is 1148 B.t.u. per lb. and its temperature is 205.9 deg. Another reference to the steam table shows that the absolute pressure of steam having a temperature of 377.6 deg. is 190 lb. per sq. in., and the heat of the liquid of such steam is 350.4 B.t.u. per lb. while the latent heat is 846.9.

Then, substituting in the formula given (on page 127) for calculating the quality of steam we have

$$Q = \frac{(1148 - 350.4) + 0.46\,(286 - 205.9)}{846.9} =$$

$$\frac{797.6 + (0.46 \times 80.1)}{846.9} = \frac{797.6 + 36.8}{846.9} = 0.9852$$

or 98.52 per cent. as the quality of steam.

BOILER EFFICIENCY

Usually the sole purpose of a steam boiler is to generate steam. To do this, heat is required and this is obtained by burning fuel in a furnace connected with the boiler. In reality, there are two distinct steps in the process of steam generation and two parts in the apparatus employed. First, heat must be generated and for this the furnace and grate when solid fuel is used are required. Second, the heat generated must be transferred to water so as to convert it into steam and for this the boiler proper is provided.

The degree of perfection or the efficiency with which each part
does its work depends partly upon its design and partly upon the
skill and care employed by the operators.

The efficiency of the boiler alone is the ratio of the heat absorbed
by the water within to the heat supplied to the heating surface.
To illustrate, if by calculation based upon the pounds of water
evaporated and the pounds of fuel actually burned, it were found
that for every 1000 B.t.u. actually liberated by the combustion of
the fuel, 740 is transferred to or absorbed by the water in the boiler
to make steam, while the balance was lost in various ways, the
efficiency of the boiler would be as 740 is to 1000, or

$$\frac{740}{1000} \times 100 = 74 \; per \; cent.$$

On the other hand, the efficiency of the boiler and grate, taken
as a whole, is the ratio of the heat absorbed by the water to the
total available heat supplied to the furnace, the latter item being
based on the number of pounds of fuel fired and the heat value of
the fuel when fired.

The difference between these two methods of calculating effi-
ciency is that in the first case the boiler is not charged with the loss
due to unburned fuel dropping through the grate, which is proper
as only the grate and not the boiler itself is responsible for loss in
this direction.   Hence, this loss is taken into consideration only
when the boiler and grate are all considered as one unit.

It is customary to state both efficiencies when making a report
of a test but the one of greater interest in every-day plant opera-
tion is the efficiency of boiler and grate.   In brief form the two
efficiencies are:

$$Efficiency \; of \; boiler \; = \frac{heat \; absorbed \; per \; lb. \; fuel \; burned}{heat \; value \; of \; 1 \; lb. \; fuel}$$

$$Efficiency \; of \; boiler \; and \; grate \; = \frac{heat \; absorbed \; per \; lb. \; fuel \; fired}{heat \; value \; of \; 1 \; lb. \; fuel}$$

A boiler test may be elaborate or simple, depending upon the
object in view.   With the elaborate test every factor possible is

taken into consideration and the greatest possible accuracy is secured. With the simple test less effort is made and fewer factors are considered. The simplest test takes into consideration only the weight of the water apparently evaporated and the weight of the fuel supplied to the furnace. In between come the happy mediums which are elaborate enough to insure reasonable accuracy and simple enough to avoid expensive complications and justifiably dispensable effort. Such a one will be herein outlined. It may be further simplified on the judgment of the man who is conducting the test. All the principles involved and all the calculations entering into the making and reporting of this test have been taken up in detail in previous lectures and it only remains for the writer to show how they all are brought into application when conducting a test.

Test Apparatus Required

The following apparatus is required for properly making a test as here outlined:

1. Equipment for measuring or weighing water evaporated.
2. Equipment for measuring or weighing fuel.
3. Two draft gages; one at damper, one at furnace.
4. Four thermometers; one for feed water, one for steam calorimeter, one for flue gases and one for air.
5. One complete flue-gas analyzing set.
6. One steam calorimeter.
7. One outfit for making proximate fuel analyses.

Weighing Feed Water

As probably has been assumed from foregoing paragraphs, one of the main factors to be determined is the weight of water evaporated or steam generated during the test. This factor can be ascertained in two ways. First, the water can be measured or weighed before it is fed to the boiler or, second, the steam given off by the boiler can be collected, condensed and measured or weighed.

The latter method is, perhaps, the more reliable because only water that has been condensed from steam will be weighed while with the first method all the water pumped into the boiler may not be evaporated during the test.   If the blowoff should be leaky some of the water might escape in that direction without being converted into steam; also the water level in the boiler might not be the same in the end as in the beginning of the test, thus causing error in the amount of work credited to the boiler.

It is seldom, if ever, possible to condense and weigh the steam from a boiler being tested because usually it would be very inconvenient and expensive to install a special condensing equipment. Besides, this method would require taking the boiler out of service which sometimes cannot be done.   However, with reasonable care the other method gives practically as reliable results.

Numerous methods of measuring or weighing the feed water can be devised and the one best to employ for any given test depends upon local conditions, size of the boiler, etc.   Ordinarily, two tanks will suffice, one for measuring or weighing the water as it is received from the heater and one to which the feed-pump suction is attached to act as a receiving or storage tank.   The tanks and the feed pump should be located as close as possible to the boiler to be tested so as to avoid radiation losses.   The most convenient arrangement is to have the measuring or weighing tank placed upon a platform directly over the receiving tank so that the discharge to the latter will be as direct and rapid as possible.   Preferably, the upper tank should rest on a set of scales so that each tankful may be actually weighed.   If this is not convenient the tank may be provided with a suitable overflow and filled to overflowing each time, the capacity having first been accurately determined by either actually measuring or weighing the contents.

If possible, the thermometer for measuring the temperature of the feed water should be inserted in the feed pipe close to the boiler by means of a mercury thermometer well.   If this cannot be done, the thermometer should be hung in the suction tank.

For measuring the fuel, if it is oil, a meter is usually employed,

although a tank arrangement similar to that for the feed water could be used, suitable precautions being provided, of course, against fire. If the fuel is solid, two or more ordinary wheelbarrows of suitable capacity will be required together with a set of ordinary platform scales. If the scales are of the portable variety, wooden runs for rolling the barrows up onto the platform and down off of it again will be found convenient.

The two draft gages, specified as item 3, while not absolutely essential, will be found instructive and helpful in analyzing results. One should be connected with the furnace and the other with the uptake on the boiler side of the damper. Any type of gage will suffice, although the more accurate it is and the closer it can be read, the better.

The only absolutely necessary thermometer specified in item 4 is that for measuring the feed-water temperature. The others may be dispensed with if small economy is any object. In this case, the steam calorimeter would also have to be dispensed with and the quality of the steam, and the temperature of air and flue gases, all of which factors influence the results, would have to be guessed at.

The cost of the thermometer for the feed water should not be very great as a range up to 212 deg. will do, because the feed water must be handled at atmospheric pressure and, hence, a temperature higher than 212 would be impossible. Thermometers for measuring the ordinary atmospheric temperatures are very cheap. Indeed, they are often given away as advertisements or souvenirs, consequently, there is little excuse for not using one during a test. It should be hung in such a location that it will indicate with fair reliability the average temperature of the air entering the boiler room.

The specifications and directions for using the thermometers for the flue gases and the steam calorimeter were given fully in previous chapters and need not be repeated here.

The function and value of the proximate coal-analysis outfit, flue-gas analysis apparatus and the steam calorimeter have also been fully discussed in previous chapters. If a test is an important

one it is advisable to send a carefully collected sample of the fuel to a commercial chemical laboratory for proximate analysis and heat-value test in order to have a check on your own work.

OBJECT OF TEST

Boiler tests may be made for almost any purpose: To test the performance of a new installation; ascertain the efficiency of the boiler under operating conditions; determine the maximum capacity that can be developed; find the value of a certain grade of fuel or to compare one grade with another; discover the effect of change in furnace design, type of grate or stoker, arrangement of baffles, etc.

When tests for comparing one set of conditions or one kind of fuel with another are made, especial care should be employed to keep the operating conditions as uniform as possible so that a perfectly fair comparison may be made. For instance, suppose a new furnace is being tried out. First, a test or series of tests with the old furnace would probably be run to discover the existing economy and then a test or series with the new equipment would be conducted to discover what improvement, if any, had been secured. Now, it would obviously be unfair to overhaul the boiler between the first and second tests or series, cleaning it thoroughly both outside and in and carefully pointing up all cracks in the setting, etc., and then credit to the new furnace the improvement in efficiency thus brought about. In the same way, it would be unfair to employ a higher grade of skill in operation during one set of tests than during the other, unless, of course, the men of the greater skill were to operate the plant continuously in the future.

On the other hand, if the boiler were to be tested to find out just what degree of efficiency was attainable, it would be poor judgment not to take every precaution possible in the way of tuning up just before the test.

Thus, the object or purpose of a test should be kept carefully in mind and the method suitably adjusted to attain the desired object as fairly and satisfactorily as possible.

Before starting a test all instruments and weighing or measuring

apparatus should be examined and put in good order and, where deemed necessary, they should be tested for accuracy. If possible, the blowoff and other water connections that can be dispensed with temporarily, such as an extra feed pipe, should be disconnected and sealed with blank flanges. This is to eliminate the danger of error due to water leaking out without being evaporated. The boiler should be examined both outside and in and a full memorandum of its condition during the test, as indicated by this preliminary examination, should be included in the report. This may be of value in explaining why the results secured are good, bad or indifferent, as the case may be. If the test is for the purpose of ascertaining the highest obtainable capacity or efficiency, the boiler, furnace and setting should be put into the best possible condition.

DURATION OF TEST

The necessary length of the test will depend on its purpose and, somewhat, on local conditions. The greater the duration the less will be the effect of the errors that occur at the beginning and ending. Where the test is run under actual working conditions a duration of 24 hr. yields data on all conditions of load and operation. However, it is not always possible or convenient to conduct a test of that length and, hence, a shorter one is often made to suffice. One of 8 hr. is about as short as is safe if any dependence is to be put upon it; a 10-hr. one is better.

STARTING AND STOPPING TEST

Unless proper care is employed errors are likely to occur at the beginning and ending of a test. Effort should be made to have conditions at the start and the finish as nearly the same as possible; the steam pressure and water level, also, the size and condition of the fire should be as nearly equal as possible.

The code of the American Society of Mechanical Engineers outlines two methods of starting and stopping. One is called the "standard" method and the other, the "alternate" method. The first-mentioned one consists of drawing the fire just before

the start and building a new one on the clean grates, dating the
start from the time a new fire is lit.

At the end the fire is burned thin and drawn, the finish being
dated at that time. This method is open to criticism as there is
considerable chance for error, due to the boiler being cooled when
the fire is drawn at the start and finish. In addition, this method
is considerably less convenient than the alternate method. The
latter is as follows:

See that the boiler has been thoroughly heated by a preliminary
run of suitable length at the working pressure. Burn the fire
low and clean it well. Then make an estimate of the thickness
and condition of the fire and make a memorandum of this. Note
the time and record this as the starting time of the test and then
proceed with periodic observation of the various pressures, tem-
peratures, etc. Stoke the fire with coal that has been weighed
and keep a record of the amount used. In the same way, keep
a record of the feed water pumped, starting with the time that is
recorded as the beginning of the test.

As soon as the test is started, clean out the ashpit thoroughly
and throw away the ashes thus collected as they are not to be
entered in the test report. Before the end of the test the fire
should be burned low, just as before the start and then cleaned
so that it will have as nearly as possible the same thickness and
condition as at the start. Likewise, bring the water level to as
nearly as possible the same height as at the start. One way to
gage the thickness of the fire is to drop the rake into it so that the
tines touch the grate bars and then note the distance they have
been buried in the fuel bed. For convenience in keeping the
water level uniform a string is tied around the gage-glass at the
level of the water at the start. With an automatic feed-water
regulator this is unnecessary but still it is a good thing to have the
string there simply as a check on the regulator.

TEST REPORT

Table 4 shows the standard form of reporting boiler tests. It
has been slightly changed and abbreviated to suit practical cases

and filled in with data from an imaginary test so that it may be taken as a model for regular use.

The number of men required to conduct a test depends upon the number of different observations to be made, the interval of time between them and the arrangement of the boiler accessories and testing apparatus; hence, no definite directions can be given on this matter. If all readings are taken every 15 min., which is the customary interval when complete data are desired, in addition to one man for measuring and recording the feed water and one man for the coal, at least one extra man will be required to analyze the flue gases and perhaps a fourth man will be needed to observe temperatures, pressures, etc. Each man should be provided with a suitable chart or paper which should, if necessary, be ruled off so that the time of each reading as well as the reading itself may be noted down without confusion and undue danger of error. At the end of the test each set of readings is added up and divided by the total number of times which that particular reading has been recorded so as to get the average, which is then entered in its proper place on the report form. The total coal and water quantities are also entered upon the report, as indicated in Table 4.

In order to present an actual practice problem with which those who wish may test their grasp of the subjects involved, only data and not results have been entered in Table 4. The results and the calculations necessary to estimate them will be given in full in the next lesson. The average temperature shown by the thermometer on the exhaust side of the calorimeter may be taken as 272 deg., for the imaginary test.

TABLE 4.—BOILER-TEST REPORT FORM

Data and results of evaporative test

      made by...................Arthur Jones and assistants
Of......A Heine type water-tube boiler
At......Plant of Smith Mfg. Co., New York City.
To determine...........Efficiency under actual operating conditions.
Kind of fuel.................................No. 2 buckwheat
Kind of furnace......................Hand fired with shaking grates
State of weather................Fair, with average temperature at 37 deg.

TABLE 4.—*Continued*

Method of starting and stopping.............................Alternate
Date of test..Feb. 13, 1913.
Duration of test...10 hr.

Dimensions and Proportions

Grate surface...............Width, 8 ft. 10 in.; length, 7 ft.; area, 62 sq. ft.
Height of furnace...34 in.
Water-heating surface..2150 sq. ft.
Superheating surface...None

Average Pressures

Steam pressure by gage........................103 (abs.) lb. per sq. in.
Draft at damper..0.9 in. of water
Draft in furnace.......................................0.6 in. in water
Difference in draft between furnace and damper...........0.3 in. of water
Difference in draft between ashpit and furnace...........0.6 in. of water

Average Temperature

Air in fire room...92 deg. F.
Feed water entering boiler....................................199 deg. F.
Gases escaping from boiler....................................540 deg. F.

Fuel

Total weight of coal as fired...................................10,372 lb.
Moisture in coal as fired.......................................7 per cent.
Total weight of dry coal supplied to furnace...........................lb.
Total weight of ash and refuse..................................1897 lb.
Percentage of ash and refuse in dry coal...............................lb.

Proximate Analysis of Coal

	Coal as fired, per cent.	Dry coal, per cent.	Combustible, per cent.
Moisture..................	7.0	....	....
Volatile matter............	3.49	....	....
Fixed carbon..............	76.35	....	....
Ash......................	13.16	....	....
Total.................	100.0	....	....

Analysis of Ash and Refuse

Combustible matter......................................per cent.
Incombustible matter.....................................per cent.

TABLE 4.—*Continued*

Fuel per Hour

Dry coal consumed per hour.......................................lb.
Dry coal per sq. ft. grate per hour ....lb.

Heat Value of Fuel, B.t.u. per Pound

	Coal as Fired	Dry coal	Combustible
By calorimeter.............	....	12,600	....
Estimated................	....	....	....

Quality of Steam

Moisture in steam.....................................per cent.
Superheat..deg.
Total weight of water fed to boiler............................83,125 lb.

Water per Hour

Water fed..lb. per hr.
Water actually evaporated (corrected for moisture in steam).....lb. per hr.
Factor of evaporation......................................
Actual equivalent evaporation................................lb. per hr.

Horsepower

Horsepower developed...
Builders' rated horsepower 220
Percentage of builders' rating, developed ....

Economic Results

Water apparently evaporated, acutual conditions per pound of coal as fired.lb.
Actual equivalent evaporation per lb. coal as fired.....................lb.
Actual equivalent evaporation per lb. dry coal fired....................lb.
Actual equivalent evaporation per lb. combustible burned...............lb.

Efficiency

Efficiency of boiler (heat absorbed per lb. comb. burned divided by
  heat value of 1 lb. comb.)................................. per cent.
Efficiency of boiler and grate (heat absorbed per pound of coal fired
  divided by heat value of 1 lb. coal)......................... per cent.

Cost of Evaporation

Cost of coal per ton of 2000 lb. delivered in furnace.................$2.90
Cost of coal used for evaporating 1000 lb. water from and at 212 deg.

TABLE 4.—*Continued*

Analysis of Flue Gases

Carbon dioxide (CO_2)...................................10.7 per cent.
Oxygen (O)... 8.7 per cent.
Carbon monoxide (CO)............................... 0.4 per cent.
Nitrogen...

Method of Firing

Kind of firing (spreading, alternate or coking)..................spreading
Average thickness of fuel bed.....................................5 in.
Average time between firings for each furnace during time when fires
   are in normal condition............................... 11 min.
Average time between leveling or breaking up................... 32 min.
Average time between cleanings................................ 5 hr.

After a test has been conducted considerable work remains to be done in figuring out the results so as to make the report complete. While it should be possible for every reader to fill in the balance of the report without further illustration, it seems desirable to present the calculations in full here to serve as a sort of review.

FUEL

The first item to be calcualted is the total weight of dry coal supplied to the furnace, which is found by simply multiplying the total weight of coal as fired by 100 minus the percentage of moisture and dividing by 100 thus:

$$\frac{10,372 \times (100 - 7)}{100} = 9646 \; lb.$$

The percentage of ash and refuse in the dry coal equals the total weight of ash and refuse taken out divided by the total weight of dry coal supplied and multiplied by 100, as follows:

$$\frac{1897}{9646} \times 100 = 19.67 \; per \; cent.$$

To calculate the proximate analysis of the dry coal from the analysis of the coal as fired, add together the percentage of volatile matter, fixed carbon and ash, divide each in turn by their sum and multiply by 100, thus:

$$3.49 + 76.35 + 13.16 = 93$$

Then, the percentage of volatile matter in the dry coal is

$$\frac{3.49}{93} \times 100 = 3.75 \; per \; cent.$$

the percentage of fixed carbon is

$$\frac{76.35}{93} \times 100 = 82.1 \; per \; cent.$$

and the percentage of ash is

$$\frac{13.16}{93} \times 100 = 14.15 \; per \; cent.$$

The same procedure is employed in calculating the analysis of the combustible matter, except in this case the percentage of ash is also left out. This analysis is: Volatile, 4.37, and fixed carbon, 95.63 per cent.

Analysis of Ash and Refuse

An actual analysis of the ash and refuse may be made in the same way and with the same apparatus employed in making the proximate coal analysis or the analysis may be estimated. This is done by subtracting the estimated total weight of real ash from the actual total weight of ash and refuse, dividing the difference by the latter and multiplying by 100. This gives the percentage of combustible matter in the ash and refuse and the difference between this figure and 100 gives the percentage of incombustible matter. The figures in the present case are

$$\frac{10,372 \times 13.16}{100} = 1365 \; lb.$$

estimated total ash and, hence,

$$1897 - 1365 = 532 \ lb.$$

combustible matter in the ash and refuse, making,

$$\frac{532}{1897} \times 100 = 28 \ per \ cent.$$

combustible matter in the ash and refuse and, hence,

$$100 - 28 = 72 \ per \ cent.$$

incombustible matter.

The average weight of dry coal consumed per hour is the total weight consumed divided by the number of hours, or,

$$9646 \div 10 = 964.4 \ lb.$$

and the pounds consumed per square foot of grate per hour is the total weight consumed per hour divided by the area of the grate in square feet, thus:

$$964.6 \div 62 = 15.55 \ lb.$$

Heat Value of Coal

To estimate the heat value of the dry coal the chart, Fig. 11 will be required. The percentage of fixed carbon in the combustible matter has just been found to be 95.63. Locating this point on the bottom of the chart and tracing a vertical line up to the curve, then across to the left margin shows that the heat value of the combustible should be about 14,900 B.t.u. per lb. As the combustible matter composes but 85.85 per cent. of the dry coal, the heat value of 1 lb. of dry coal will be but 85.85 per cent. of that of 1 lb. of combustible, or,

$$\frac{14,900 \times 85.85}{100} = 12,792 \ B.t.u.$$

and, as the combustible matter in 1 lb. of coal as fired equals only 79.84 per cent., the heat value of 1 lb. of coal as fired is only

$$\frac{14,900 \times 79.84}{100} = 11,896 \ B.t.u.$$

To estimate the heat value of the combustible from the heat value of the dry coal as shown by the calorimeter test it is simply necessary to invert the latter part of the above process. The 12,600 B.t.u. shown by the calorimeter to be the heat value of 1 lb. of dry coal is really the heat value of the 0.8585 lb. of combustible contained in a pound of coal. Hence, the heat value of one whole pound of combustible must be

$$12,600 \div 0.8585 = 14,677 \; B.t.u.$$

The heat value of the coal as fired is figured from the heat value of the dry coal, as shown by the calorimeter in exactly the same manner as in the case of the estimated values just illustrated. Thus, the heat value of the coal as fired is

$$\frac{12,600 \times 93}{100} = 11,718 \; B.t.u. \; per \; lb.$$

MOISTURE IN STEAM

The quality of the steam may be estimated by the formula:

$$Q = \frac{(H - h) + 0.46 \, (T - T_1)}{L}$$

For the conditions of the test H, the total heat of dry-saturated steam at atmospheric pressure, equals 1150.4 B.t.u. per lb.; h, the heat of the liquid corresponding with the pressure carried in the boiler, equals 300.6 B.t.u. per lb.; T, the temperature on the discharge side of the steam calorimeter, equals 272 deg. F.; T_1, temperature of saturated steam at atmospheric pressure, equals 212 deg., and L, the latent heat of steam at the boiler pressure, equals 886.3 B.t.u. per lb. Substituting these values in the formula we have

$$Q = \frac{(1150.4 - 300.6) + 0.46 \, (272 - 212)}{886.3}$$

$$= \frac{849.8 + 27.6}{886.3} = 0.99$$

or 99 per cent., which means that there was

$$100 - 99 = 1 \; per \; cent.$$

of moisture in the steam.

The water fed to the boiler per hour is the total water fed divided by the number of hours, thus:

$$83,125 \div 10 = 8312.5 \; lb.$$

The water actually evaporated per hour is the water fed per hour multiplied by the quality of the steam expressed as a decimal fraction, or,

$$8312.5 \times 0.99 = 8229.4 \; lb.$$

The formula of calculating the factor of evaporation, is

$$F = \frac{(H - t) + 32}{970.4}$$

For the conditions of the test H, the total heat above 32 deg. in the steam at boiler pressure, equals 1186.9 B.t.u. per lb., and t, the temperature of the feed water, is 099 deg. Substituting in the formula, we have

$$F = \frac{(1186.9 - 199) + 32}{970.4} = 1.051$$

The actual equivalent evaporation per hour is the actual evaporation per hour multiplied by the factor of evaporation, thus:

$$8229.4 \times 1.051 = 8649 \; lb.$$

The horsepower developed is the average actual equivalent evaporation per hour divided by 34.5; hence, the horsepower developed in the present test was

$$8649 \div 34.5 = 250.7$$

The percentage of builders' rating developed is found by divid-

ing the horsepower actually developed by the builders' rating and multiplying by 100, thus:

$$\frac{250.7}{220} \times 100 = 114 \text{ per cent.}$$

The water apparently evaporated per pound of coal as fired under actual conditions equals the water actually fed per hour divided by the weight of coal per hour as fired, or,

$$8312.5 \div 1037.2 = 8.01 \text{ lb.}$$

The actual equivalent evaporation per pound of coal as fired equals the above figure multiplied by the quality of the steam (expressed as a fraction) and the factor of evaporation, thus:

$$8.01 \times 0.99 \times 1.051 = 8.33 \text{ lb.}$$

The actual equivalent evaporation per pound of dry coal fired equals the actual equivalent evaporation per hour divided by the number of pounds of dry coal supplied per hour, or,

$$8649 \div 964.6 = 8.97 \text{ lb.}$$

In estimating the analysis of the ash and refuse we found that a total of 532 lb. or 53.2 lb. of combustible matter fell through the grate to the ashpit.

The dry coal fired per hour weighed 964.6 lb. and of this 85.85 per cent., or 828.1 lb., was combustible matter. Hence, the percentage of combustible matter falling to the ashpit was

$$\frac{53.2}{828.1} \times 100 = 6.42 \text{ per cent.}$$

As the combustible matter comprised 85.85 per cent. of the dry coal and as all the heat was furnished by the combustible matter, it is evident that the 8.97 lb. actual equivalent evaporation per pound of dry coal fired was really 8.97 lb. actual equivalent evaporation per 0.8585 lb. combustible matter fired. Hence,

the actual equivalent evaporation per pound of combustible fired
must be

$$\frac{8.97}{0.8585} = 10.45 \ lb.$$

But, 6.42 per cent. of the combustible fired fell into the ashpit,
was unburned and, hence, supplied no heat. Therefore, the
10.45 lb. actual equivalent evaporation per pound of combustible
fired is 10.45 lb. per

$$\frac{100 - 6.45}{100} = 0.9355 \ lb.$$

of combustible burned, or

$$10.45 \div 0.9355 = 11.17 \ lb.$$

per pound of combustible burned.

The heat absorbed per pound of combustible burned equals
the number of pounds of actual equivalent evaporation per pound
of combustible burned multiplied by the latent heat of steam at
atmospheric pressure, or 970.4. Then, in the present case the
heat absorbed equals

$$11.17 \times 970.4 = 10,839 \ B.t.u.$$

and, as the heat value of a pound of combustible was found to be
14,677 B.t.u., the efficiency of the boiler is

$$\frac{10,839}{14,677} \times 100 = 73.58 \ per \ cent.$$

In a similar way the efficiency of the boiler and grate equals the
actual equivalent evaporation per pound of coal fired, multiplied
by 970.4 and divided by the heat value of 1 lb. of coal and all
multiplied by 100, thus:

$$\frac{8.97 \times 970.4}{12,600} \times 100 = 69 \ per \ cent.$$

If the actual equivalent evaporation per pound of coal as fired

was 8.33 lb., the number of pounds of coal as fired required to evaporate 1000 lb. of water from and at 212 deg. was

$$1000 \div 8.33 = 120$$

and as this quantity is

$$\frac{120}{2000} \times 100 = 6 \ per \ cent.$$

of one ton, the cost of evaporating 1000 lb. of water was

$$\frac{2.90 \times 6}{100} = \$0.174$$

HEAT BALANCE

In preceding chapters a method was given for conducting a boiler test, making and estimating the efficiency and economic results. After a test has been made the owner or engineer may be dissatisfied with the showing made. He may have been justified in expecting a better efficiency when the design, arrangement and condition of the boiler, furnace setting, etc., are taken into consideration. The test report alone does not show him in what particular the operation was poor, it simply gives final results. To get fuller information as to how the operation can be improved it is necessary to analyze the distribution of the heat contained in the coal. Perhaps in every pound of coal thrown into the furnace there was 14,000 B.t.u. available. If all this heat could be put into the water, an efficiency of 100 per cent. would be obtainable.

Unfortunately, this is impossible—some loss is bound to take place. At the very beginning, some of the burnable matter falls through the grate with the ash. Hence, all the combustible matter of the original pound of coal is not burned and, consequently, the full 14,000 B.t.u. is not generated. Next, the moisture in the coal must be evaporated and superheated and all the heat that such moisture carries out with the flue gases is lost.

The air fed into the furnace all passes out again to the chimney. True, a part of it has undergone a change (the oxygen combining with the hydrogen and carbon of the fuel) but it is all there nevertheless. This air leaves the boiler at a considerably higher temperature than that at which it entered. The heat added to it was obtained from the coal—and nowhere else. Hence, here is another loss. And so it goes; some heat radiates from the boiler and setting, and some more heat is lost through the incomplete combus-

tion of the carbon in the fuel. Some heat is lost through unburned particles of combustible matter passing up the stack as soot, and some is lost because all the heat created by the combustion of the hydrogen in the fuel cannot be recovered in the boiler.

An itemized statement in B.t.u. and percentage of all these losses together with the quantity of heat absorbed by the water in the boiler to make steam is called a heat balance. To itemize each loss individually would necessitate considerable trouble in the way of obtaining the required data so only six divisions are usually made:

(a) Loss due to moisture and hydrogen in coal.
(b) Loss due to heat carried away by dry flue gases.
(c) Loss due to incomplete combustion.
(d) Loss due to coal dropping through grates.
(e) Heat unaccounted for (this item includes all losses not taken into consideration in the four foregoing items).
(f) Heat put into the water.

Item (a) is made up of two factors: 1, the loss of heat required to change the moisture in the coal into steam at the temperature of the gases leaving the boiler and, 2, the loss due to the fact that all of the heat generated by the combustion of the hydrogen of the fuel cannot be used for making steam in the boiler. When hydrogen burns it forms water in the shape of highly superheated steam which in the fuel calorimeter is condensed so that the latent heat of this steam passes into the cooling water surrounding the bomb and is credited to the coal. In actual use in the boiler, however, the steam formed by the combustion of the hydrogen is partly cooled by contact with the heating surface of the boiler, but it is not cooled sufficiently to condense and, consequently, it passes off in a superheated condition at the temperature of the chimney gases. Hence, the additional heat it would give up if cooled down to ordinary temperatures and condensed is lost.

The heat given up when a pound of superheated steam at atmospheric pressure is condensed and cooled from 500 deg. to 70 deg. is exactly equal to the heat required to evaporate and superheat a pound of water from 70 to 500 deg. Hence, for simplicity and

convenience it is customary to calculate the amount of water that
would be formed from the estimated quantity of hydrogen in the
coal and add this to the amount of moisture in the coal as shown by
the proximate analysis and then calculate the heat required to
raise the total quantity to the boiling point, convert it into steam
and superheat it to the temperature of the escaping gases.

The first step, then, is to estimate the percentage of hydrogen
in the coal, for it is seldom that an ultimate analysis is avail-
able in commercial practice. The following formula, originated
by Professor Diederichs, gives the approximate total hydrogen
in the combustible matter:

$$H = v \left(\frac{7.35}{v + 10} - 0.013 \right)$$

where

H = percentage by weight of hydrogen in the combustible
matter;

v = percentage by weight of volatile matter in the combust-
ible matter.

For illustrating the application of this formula and other cal-
culations required in constructing a heat balance the data and
results of the imaginary test reported in a previous chapter will
be used. In the calculations in the last chapter it was found that
the percentage of volatile matter in the combustible was 4.37.
Substituting in the foregoing formula we have

$$H = 4.37 \left(\frac{7.35}{4.37 + 10} - 0.013 \right) = 2.18 \ per \ cent.$$

hydrogen in the combustible matter. As there is only 79.84
per cent., or 0.7984 lb. combustible in each pound of coal as fired,
the percentage of hydrogen in the coal as fired is only

$$(2.18 \times 79.84) \div 100 = 1.74 \ per \ cent.$$

or 0.0174 lb. hydrogen per pound of coal as fired.

It was shown that the combustion of every pound of hydrogen
results in the production of 9 lb. of water. Consequently, the
combustion of 0.0174 lb. of hydrogen results in the production of

$$0.0174 \times 9 = 0.157 \ lb.$$

The proximate analysis of the coal used in the test showed that in each pound of coal as fired there was 0.07 lb. of water. Then, the loss due to the hydrogen and moisture in the coal as fired is equal to the heat required to evaporate and superheat

$$0.157 + 0.07 = 0.227\ lb.$$

of water from 92 to 540 deg., the temperatures given in the test report.

The heat required to raise this quantity of water from 92 deg. to the boiling point, 212 deg., is

$$(212 - 92) \times 0.227 = 27.24\ B.t.u.$$

The heat required to change this water into steam from and at 212 deg. (latent heat) is

$$970.4 \times 0.227 = 220.28\ B.t.u.$$

And, assuming the specific heat of superheated steam to average 0.46, the heat required to superheat the steam from 212 to 540 deg. is

$$(540 - 212) \times 0.227 \times 0.46 = 34.25\ B.t.u.$$

Hence, the total loss per pound of coal as fired, due to the hydrogen and moisture, is

$$27.24 + 220.28 + 34.25 = 282\ B.t.u.$$

As the heat value of the coal as fired was 11,718 B.t.u. per lb. this loss expressed in percentage is

$$(282 \div 11{,}718) \times 100 = 2.4\ per\ cent.$$

In the present case this loss is not very high, because the coal used was of the anthracite grade in which the percentage of moisture and hydrogen never runs very high. But, with other grades, especially the bituminous and lignite, the loss runs considerably higher.

Item (b) of the heat balance is the most important because it is the largest and its magnitude depends greatly upon the skill and care used in operation.

A formula for estimating the heat lost up the chimney per pound of coal burned is:

$$L = 0.24\ \ W\ (T - t)$$

where,

    L = B.t.u. lost up the chimney per pound of fuel burned;

    W = weight of flue gas formed per pound of fuel burned;

    T = temperature of the gases leaving the boiler;

    t = temperature of the air entering the furnace.

The weight of the flue gases formed per pound of coal burned is estimated by another formula as follows:

$$W = 3.032\, C\left(\frac{N}{CO_2 + CO}\right) + (1 - A)$$

where

$$C = \text{weight of total carbon in the fuel as fired;}$$

$N, CO_2 \text{ and } CO$ = percentage by volume of nitrogen, carbon dioxide and carbon monoxide, respectively, in the flue gases;

$$A = \text{weight of ash in the fuel as fired.}$$

When the volatile matter in the combustible amounts to 12 per cent. or more the total carbon in the coal as fired is found with the aid of the chart, Fig. 11. Where it runs less, it is safe enough to assume that the volatile carbon is approximately one-third of the volatile matter. Thus, in the present case, the volatile carbon in the coal as fired would be

$$3.49 \div 3 = 1.16 \text{ per cent.}$$

and the total carbon would be, therefore,

$$76.35 + 1.16 = 77.51 \text{ per cent.}$$

or 0.7751 lb. per lb. of coal as fired. Substituting in the foregoing formula this value and the values for the flue gases as given in the test report we have:

$$W = 3.032 \times 0.7751\left(\frac{80.2}{10.7 + 0.4}\right) + (1 - 0.1316) = 17.85 \text{ lb.}$$

And applying this factor in the formula for heat loss we have

$$L = 0.24 \times 17.86\,(540 - 92) = 1920 \text{ B.t.u.}$$

per pound of coal burned, carried up the chimney by the flue gases. Expressed in percentage this equals

$$(1920 \div 11{,}718) \times 100 = 16.38 \text{ per cent.}$$

The method of calculating item (c) was given in Chapter VIII. The formula is,

$$L' = 10,150 \left(\frac{CO}{CO + CO_2} \right) C$$

in which L' equals the heat loss due to incomplete combustion per pound of coal burned and expressed in B.t.u., and the other symbols represent the same values as before. The heat loss in the present case is

$$L' = 10,150 \left(\frac{0.4}{0.4 + 10.7} \right) 0.7751 = 283 \; B.t.u.$$

or

$$(283 \div 11,718) \times 100 = 2.41 \; per \; cent.$$

In the last chapter it was estimated that there was 532 lb. of combustible matter in the ash and refuse. As the heat value of the combustible was found to be 14,677 B.t.u. per lb., the total heat loss due to unburned coal dropping through the grates was

$$14,677 \times 532 = 7,808,164 \; B.t.u.$$

And, consequently, the loss per pound of coal fired (item (d) of the heat balance) was

$$7,808,164 \div 10,372 = 753 \; B.t.u.$$

which, expressed in percentage equals,

$$(753 \div 11,718) \times 100 = 6.43 \; per \; cent.$$

Item (e) is the difference between the heat value of the coal as fired and the sum of all the other items.

The efficiency of the boiler and grate was found to be 68.98 per cent. In other words,

$$(11,718 \times 68.98) \div 100 = 8083 \; B.t.u.$$

was put into the water in the boiler to make steam. Then, item (e), representing all other losses or losses unaccounted for must be,

$$11,718 - (282 + 1920 + 283 + 753 + 8080) = 397 \; B.t.u.$$

$$(397 \div 11,718) \times 100 = 3.39 \; per \; cent.$$

All the items of a heat balance are usually arranged in tabular form, thus: ·

HEAT BALANCE

Heat value of 1 lb. coal as fired $= 11,718$ B.t.u.

Distribution of heat	B.t.u.	Per cent.
(a) Loss due to moisture and hydrogen in coal.......	282	2.41
(b) Heat carried away by flue gases................	1,920	16.38
(c) Loss due to incomplete combustion.............	283	2.41
(d) Loss due to unburned coal dropping through grates	753	6.43
(e) Losses unaccounted for.........................	397	3.39
(f) Heat absorbed by boiler........................	8,080	68.98
Total.......................................	11,718	100.00

CHAPTER X

FEED-WATER TREATMENT

A cardinal requisite to high boiler efficiency and consequent low operating cost is a clean boiler both outside and in. The man who neglects to protect the outside of the heating surface from the accumulation of slag, soot, etc., and the inside from accumulation of scale, etc., simply because it is a bother to do so, is not living up to his opportunities.

The main sources of feed-water supply are wells, rivers, ponds, lakes, etc. The great primary sources of supply to these secondary sources are the oceans which cover about three-quarters of the earth's surface. This water contains so much impurities that it is unfit to drink or to use in a boiler until it is purified. The chief impurity is salt, the chemical name of which is sodium chloride and the chemical symbol is NaCl. The letter S could not be used in the symbol because S, you will remember, is the symbol for sulphur, so the abbreviation Na, of the Latin name *natrium*, is employed.

A gallon of sea water contains about 1.75 lb. of salt. To illustrate how difficult it would be to operate on sea water, it has been estimated that a 72-in. by 18-ft. tubular boiler (150 hp.), if it could be operated continuously at its rated capacity on sea water, would fill solid to the water line with salt in about 48 hr.

For stationary boiler plants, nature herself performs part of the purifying process. The heat of the sun causes ocean water to evaporate and rise in the atmosphere to form clouds. As salt does not vaporize at ordinary temperatures it remains behind, while only the pure water itself rises in the air. Changes in the atmospheric temperature and pressure cause the vapor to condense to the liquid form again and fall to earth as rain. Rain water is almost absolutely pure.

Water has great powers for dissolving substances. Almost everything in the world can be dissolved in it.   Some substances dissolve very slowly and only in exceedingly minute quantities while others dissolve very quickly and in large quantities.   In sinking into the ground or running off to the river or lake, the pure rain water dissolves substances that it happens to meet, thus becoming impure.   The quantity of any given substance which the water will dissolve and carry along with it depends upon the readiness with which the substance dissolves and the length of time the water is in contact with it.

Of the many substances that may exist in a dissolved state in water, we are interested in only those which tend to cause scale, sediment and corrosion.   These in themselves are quite numerous and a full study of and treatment for them all can be made only by a trained chemist.   Hence, when a feed water is causing trouble it is very often advisable to submit a sample to a competent and reliable chemist or company for analysis and prescription or treatment.   However, as there are a few impurities which cause the greater part of the trouble encountered, a short study of these, including an explanation of their action, how they are detected, their quantity estimated and a neutralization or elimination effected, may be worth while.

COMMON IMPURITIES

The commonest impurities found in water are calcium carbonate, magnesium carbonate, calcium sulphate and magnesium sulphate—rather formidable names but really not such formidable substances, because all four of them possess only two elements that can possibly be new or strange to the students of this course.

CALCIUM CARBONATE

The chemical formula for calcium carbonate is $CaCO_3$.   This means that it is composed of one combining weight of calcium,

one of carbon and three of oxygen. The calcium is the only element that is new to us. It is a metal but one which is never found in its pure or uncombined state in nature because it is a very active element and readily forms compounds with other elements. Its compounds, however, are very common substances. One of its most familiar and useful compounds is ordinary lime, such as used for making mortar and plaster. The chemical formula for this substance is CaO and its chemical name is calcium oxide. When water is added to lime, making slack lime, the formula is

$$CaO + H_2O = CaO_2H_2$$

Pure calcium can be produced artificially by reducing one of its compounds. When pure and fresh a piece of it looks like zinc. But when exposed to the air a while it becomes yellowish and finally gray or white in color, due to a reaction between it and the oxygen and moisture of the air resulting in a layer of slaked lime (CaO_2H_2). The combining weight of calcium is 40.1 and, it will be remembered, the combining weights of carbon and oxygen are 12 and 16, respectively. Then, as its formula indicates, calcium carbonate is composed of these three elements in proportion of 40.1 lb. of calcium, 12 lb. of carbon and $3 \times 16 = 48$ lb. of oxygen. Chalk, limestone and marble are all almost pure calcium carbonate.

Pure water is capable of dissolving calcium carbonate in very small quantities—10,000 parts of water are required to dissolve one part of calcium carbonate. That is, to dissolve 1 lb. of chalk would require 10,000 lb. of water or some 1200 gal. and a peculiar fact is that calcium carbonate is less soluble in hot water than in cold. If this was the only rate at which calcium carbonate could get into a boiler (1 lb. per 10,000 of water) there would not be much difficulty in coping with it. But it is not. Carbonic acid or carbon dioxide (CO_2), our old friend which is formed when carbon is burned, can be absorbed by or dissolved in water, and in its descent through the air and travels on and in the earth water does absorb some of this gas. Now, when water containing carbon dioxide flows over chalk, limestone, rocks, marble or other sub-

stances mainly composed of calcium carbonate, the carbon dioxide, water and calcium carbonate all get together and form a substance known as calcium bicarbonate—$CaH_2(CO_3)_2$—a substance which water can dissolve and carry in solution in quite large quantities.

This calcium bicarbonate, however, is not a very stable compound. When the water containing it is heated to 180 deg. F. or more, it begins to break up into its three components—CO_2, water, and calcium carbonate. The CO_2 now changes (due to the heating of the water) into its gaseous form and, rising through the water in bubbles, escapes in the atmosphere. This leaves an excess of calcium carbonate in the water, which, as was just stated, is only slightly soluble in water. This excess, therefore, settles to the bottom as a fine powder.

When a substance is suddenly changed to its solid form and settles out of the liquid in which it was dissolved (as in the case just described) it is said to have been "precipitated" or "thrown down" and the process is called precipitation.

The foregoing paragraphs show why some boilers are found to contain internal coatings of soft sand-like or mud-like material. They have been fed with water carrying calcium bicarbonate which the heat has changed back to calcium carbonate. As the latter is a solid which cannot be vaporized (just like the sea salt) it is left in the boiler while the water which carried it evaporates and passes off as steam to the engine or other destination. Each gallon of water fed in leaves its particles of solid calcium carbonate behind and unless blown down and cleaned often enough the boiler would become choked.

This calcium carbonate by itself does not form a hard troublesome scale, but simply a loose mud-like coating which can easily be washed off the tubes and shell. In fact, a large part of it settles to the bottom of the boiler or to the mud drum of its own accord, and can easily be blown out. But, as will be seen later, when certain other impurities are present in the water, the calcium carbonate is cemented into a troublesome scale along with these other impurities.

MAGNESIUM CARBONATE

The second commonly encountered impurity in water is magnesium carbonate. Its chemical formula is $MgCO_3$. It will be noticed that the only difference between this formula and that of calcium carbonate is that Mg in the present case takes the place of Ca in the previous one. Both are carbonates, due to their carbon and oxygen content.

Magnesium is also a metal and in its pure state has a bright silvery white appearance. Like calcium it never exists pure in nature as it has very strong tendencies to combine with other elements. One of its compounds which is familiar to all is Epsom Salts. The chemical name for this compound is magnesium sulphate, which is included in our list of commonly encountered impurities and about which more will be stated later on. Other familiar substances with magnesium in their makeup are talc, asbestos and meerschaum. Magnesia pipe covering is composed principally of magnesium carbonate. The combining weight of magnesium is 24.4.

In nature, magnesium carbonate exists quite extensively and is known as magnesite. It also exists in combination with calcium carbonate, this compound being known as dolomite. Magnesium carbonate will not dissolve in pure water. But when water containing CO_2 comes in contact with it, magnesium bicarbonate—$MgH_2(CO_3)_2$—is formed and this, like the calcium bicarbonate, is quite soluble in water. When heat is applied, the bicarbonate breaks up and the CO_2 escapes as a gas, just as in the case of the calcium bicarbonate. The passing off of the CO_2 leaves behind an insoluble substance called magnesium hydroxide whose chemical formula is $Mg(OH)_2$. This precipitate being light, settles out of the water but slowly, and in the boiler where the circulation is strong it has a tendency to stay suspended and cause trouble through priming. Another bad quality of this precipitate is its cementing power, which is so great that the stuff is used for making cement for commercial purposes. When it mixes with the other-

wise loose particles of precipitated calcium carbonate, a brittle
scale results, which cakes on the boiler surfaces.

CALCIUM SULPHATE

The chemical formula for calcium sulphate is $CaSO_4$. All
the elements in this compound are familiar to the readers of these
lessons so it is only the compound itself that need be studied.
One of the common substances composed of calcium sulphate is
plaster of paris.   Unlike the carbonates, calcium sulphate does not
require CO_2 to assist it to dissolve.   Pure water will take just as
much as water heavily charged with CO_2.   A fact that is very
important to the engineer is that calcium sulphate is more soluble
in cool water than in hot.   According to some authorities the
temperature at which the most calcium sulphate can be dissolved
in a given quantity of water is about 90 deg. F.   As the tempera-
ture increases the solubility of this compound gradually decreases
until at 302 deg. it is practically insoluble.   Because of this char-
acteristic and the fact that the scale it forms is very hard and has
great cementing powers over other substances, calcium sulphate
is a troublesome and dangerous impurity.   Usually it can be
fought only with suitable chemical compounds.

MAGNESIUM SULPHATE

The fourth and last impurity we are going to consider is mag-
nesium sulphate, although as was stated that there are several
others that are sometimes encountered.   The chemical formula for
this compound is $MgSO_4$ which, as the name indicates, is the same
as that for calcium sulphate except that magnesium takes the place
of the calcium.   And, like the other sulphate, it dissolves more
easily in cool water than in hot.   At 302 deg. it precipitates or
deposits as a monohydrated salt, the formula being $MgSO_4H_2O$.
It will be noted that the elements composing water (H_2O) have
been added.   This fact is indicated in the name by the word

monohydrated, mono meaning one and hydrated meaning watered. As used, the word means that one molecule of water has been added to or joined with each molecule of magnesium sulphate.

By itself magnesium sulphate does not really form a scale but its presence in feed water is undesirable because it interferes with the treatment of the impurities that do form scale.

METHODS OF TREATMENT

Water containing impurities detrimental to good boiler operation can be treated in several ways, the method to be employed depending on the nature of the impurities contained. For removing mud and sediment the water may be filtered or it may be allowed to stand and "settle" before it is fed into the boiler. For what is called temporary hardness the water may be heated to 180 deg. or more. Temporary hardness is defined as hardness which can be eliminated by heating to or nearly to the boiling point (212 deg.), and is caused by the carbonates which, it will be remembered, are precipitated by heat. Hardness can be detected and its degree estimated by the effect it has upon soap.

For permanent hardness more intense heat (to at least 302 deg.) may be applied as on a closed heater or chemicals may be employed. It is the sulphates that cause permanent hardness because mere boiling at atmospheric pressure does not eliminate them.

These two terms, temporary hardness and permanent hardness, are old names invented long ago when chemistry was not as well understood as it is today. People found that water from certain sources made soap curdle instead of producing a lather. Such water they called hard. Next, they discovered that boiling sometimes improved the water; consequently such water was said to have temporary hardness. Sometimes, however, the water was only slightly or not at all improved and such water was said to have permanent hardness.

Feed water may be treated with chemicals either outside or within the boiler, the former being preferable, because the impurities are eliminated before the water is fed to the boiler and so blowing down and cleaning are required less frequently. When treatment is administered before the water is fed it is advisable to provide chemicals for the elimination of both the carbonates and sulphates, if both are present. But when treatment is administered after the water is fed only a chemical for the sulphates is required, because the heat takes care of the carbonates.

TREATMENT FOR CARBONATES

Calcium carbonate can be precipitated before the water is fed to the boiler by adding to it the proper quantity of lime, slaked lime or caustic soda.

The chemical formula for lime is CaO and that for slaked lime is CaO_2H_2, and when either of these is put into water containing calcium carbonate (in the form of calcium bicarbonate, due to the presence of CO_2) a chemical reaction takes place in which the calcium of the lime joins the calcium, carbon and oxygen of the bicarbonate, producing two parts of calcium carbonate and the hydrogen of the bicarbonate joins the oxygen and hydrogen of the slacked lime producing two parts of water. The equation is

$$CaH_2 (CO_3)_2 + CaO_2H_2 = 2\ CaCO_3 + 2\ H_2O$$

The calcium carbonate, being insoluble, drops out or is precipitated.

The chemical formula for caustic soda, whose chemical name is sodium hydrate, is NaOH. If this is put into the water instead of the lime, part of the carbon and oxygen of the calcium bicarbonate combines with it to form sodium carbonate (Na_2CO_3) which is easily soluble in water. The calcium bicarbonate being robbed of part of its carbon and oxygen changes back to calcium carbonate and, being insoluble, it precipitates as before.

The treatment for magnesium carbonate is exactly the same as for the calcium carbonate.

TREATMENT OF SULPHATES

Calcium sulphate ($CaSO_4$) can be precipitated by means of sodium carbonate, or soda ash as it is called commercially. The chemical formula for the latter is Na_2CO_3. When this compound
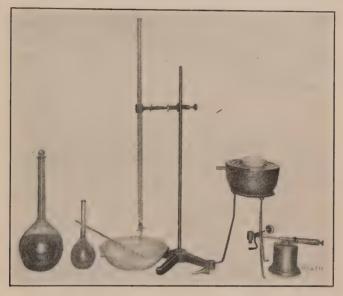

FIG. 25.—Apparatus required for proximate water analysis.

is put into water containing calcium sulphate the sulphur and one-quarter of the oxygen in the calcium sulphate change places with the carbon in the sodium carbonate, producing sodium sulphate and calcium carbonate. The first of these is soluble and harmless and the second, being insoluble, precipitates as before.

The treatment for magnesium sulphate is exactly the same as for calcium sulphate.

To secure desirable results in treating feed water the quantity of compound supplied must be proportioned according to the

amount of scale-forming impurities present. To estimate the amount of impurities present necessitates an analysis of the water. Generally speaking, a water analysis can only be made by a trained chemist. It can be attempted by others, but the results obtained would in most cases be so inaccurate as to be useless. The engineer can, however, make an approximate analysis which is of some value in indicating the character of the water and if the analysis is made with care and the water does not contain impurities that complicate its nature too much, the kind and quantity of scale-preventing compound needed can be estimated.

The following method of approximate water analysis is based on that given by John B. C. Kershaw, in "Fuel, Water and Gas Analysis," published by D. Van Nostrand Co.

Test Apparatus

Assuming that the reader possesses the apparatus for making the proximate fuel analysis, as listed, the following additional equipment, most of which is shown in Fig. 25, is required for making the proximate water analysis as here outlined:

1 Copper water bath, 6 in. diam.................................	$1.50
1 Measuring flask (200 c.c. capacity).............................	0.35
1 Porcelain dish (22 oz. capacity)................................	1.00
1 Glass stirring rod..	0.10
1 Burette, graduated in $\frac{1}{10}$ c.c (50 c.c. capacity)...................	2.00
1 Funnel for filling burette......................................	0.10
1 Support or stand for burette (adjustable)........................	0.80
1 Measuring flask (100 c.c. capacity).............................	0.90
1 Porcelain dish (about 50 c.c. capacity).........................	0.15
1 Glass funnel for filtering (4-in.)...............................	0.20
1 Package of filter paper (8-in., 1.00 sheets).....................	0.35
	$7.45

The following chemical solutions are also required:

2 oz. concentrated solution methyl orange........................	$0.50
1 liter—one-fifth normal standardized solution hydrochloric acid	1.40
1 liter—one-fifth normal standardized solution sodium carbonate.....	1.40
2 oz. alcoholic solution phenol-phthalein	0.50
	$3.80

If the reader does not possess proximate fuel-analysis apparatus it will also be necessary to secure a bunsen burner or an alcohol or gasoline lamp (such as is shown in Fig. 25) and an iron tripod or adjustable iron stand for supporting the water bath.

COPPER WATER BATH

The copper water bath, shown on the tripod in Fig. 25, is employed when evaporating a sample of water under conditions requiring a uniform heat at 212 deg. F. The bath is fitted with a lid composed of rings of various diameters so that the vessel containing the sample may be conveniently supported over the boiling water. A vent or spout at the side and just below the top permits the steam to escape without inconvenience to the analyst.

MEASURING FLASK

As the name implies, a measuring flask is used to measure out samples or reagents when accuracy is important. Its neck is small in diameter, and has a fine line around it to which level the liquid to be measured is poured.

BURETTE

The name burette should be familiar to the reader, as we employed one in measuring flue gas when making an analysis with the Orsat apparatus. As may have been surmised, "burette" means measuring vessel. In the present case the burette is employed to measure liquids.

Acids neutralize alkalies and *vice versa*. For instance, water containing a quantity of some acid has certain definite characteristics whereby its acid nature can be recognized. It will corrode or eat away certain metals, say, iron, and it will, generally, change a sensitized paper called litmus paper from blue to red. Now, if a certain definite quantity of alkali is added to this water the latter will lose its acid characteristics—because the alkali has neutralized the acid it contained by a chemical action between them. If

more alkali be added so that the water now contains a quantity in excess of that which was required to neutralize the acid, other characteristics will be acquired.   A definite quantity of alkali is required to neutralize a given quantity of acid and *vice versa*. For illustration, if a gallon of water contained, say, an ounce of a given acid, hydrochloric, for instance, it would be found that a definite amount of some alkali, say, sodium hydrate, would be required to neutralize this acid.

When the amount of contained acid is known, the amount of the required alkali can be calculated.   Hence, when the amount of the acid is unknown, but by experiment the required amount of alkali is ascertained, it is possible to calculate therefrom the quantity of acid neutralized.

This principle is extensively made use of in chemistry.   When analyzing water certain chemicals are added to the sample being analyzed and the amount of such chemicals required to produce a certain change is measured as accurately as possible.   This is the purpose of the burette; it is made long and of small diameter so that the quantity of liquid contained before and after some has been let out can be measured closely.   When a person adds chemicals to a sample by means of the burette and measures the quantity required to produce a certain change in the character of the sample, for the purpose of estimating its original make-up, he is said to titrate the sample.   If it is sodium hydrate he happens to be adding he is said to be titrating with sodium hydrate.

When emptying the burette of one compound and filling with another, first rinse the burette with distilled water and then pour in or rinse with a little of the new compound to be used and drain this out again before the main bulk of the new compound is filled in.

INDICATORS

When titrating a sample of water with a certain chemical it is often necessary or convenient to first put some other compound into the water for the purpose of indicating by change in color when the point of neutralization has been reached.   When a

compound is employed for this purpose it is called an indicator. Methyl orange and phenol-phthalein are used as indicators when titrating with hydrochloric acid or sodium-carbonate solutions to ascertain alkalinity or acidity.

HYDROCHLORIC ACID SOLUTION, ETC.

The accuracy of results when titrating depends upon the accuracy in measuring the sample, the accuracy in preparing the titrating fluid, the accuracy in reading the amount of titrating solution required and the accuracy in determining the point when neutralization has been effected. As it is important to get the strength of the titrating fluids as nearly correct as possible it is recommended that the one-fifth normal standardized solution of hydrochloric acid and of sodium carbonate be purchased ready made up. This will save bother and trouble and insure a greater accuracy than can be obtained under average conditions where proper facilities for best work are not present.

The bottles containing the solutions should always be kept well stoppered so that the strength will not change due to evaporation.

COLLECTING SAMPLE

Care must be exercised when collecting the sample to be analyzed. If the water is in an agitated condition a clean bottle or jar can be dipped into the tank or reservoir at almost any point and filled in the ordinary way. If it is more convenient to tap the supply main, a good arrangement is to allow a small stream of water to run into a clean barrel or tub continuously and dip the sample therefrom. The main thing is to be sure that the bottle to contain the sample and the barrel or tub, if any is employed, are clean, and will not pollute the water with foreign matter which it does not contain naturally. A sample of from 2 qt. to 1 gal. is sufficient.

TEST FOR ALKALINITY

The first step of the analysis is to test whether the water is alkaline or acidulous in nature. Usually it is alkaline, but some-

times, when the water comes from boggy land, it may be slightly acid in character.

To test for alkalinity fill the 200-c.c. measuring flask, first seeing that it is thoroughly clean, with the test water, so that the level is exactly at the line which will be found around the neck of the flask. Empty this water into the clean 22-oz. basin and rinse the flask with distilled water, putting the rinsings into the basin also.

Distilled water may be purchased by the bottle, or if much is to be used, a home-made or purchased still may be found more economical.

Add to the 200 c.c. of test water in the basin two drops of the concentrated solution of methyl orange. Next, put into the burette some of the one-fifth normal standardized solution of hydrochloric acid and read the level at which the acid stands with great care and as accurately as possible. Now, titrate by opening the cock of the burette a small amount, allowing some of the acid to fall into the basin of test water drop by drop, stirring the water all the while with the glass rod, until the color of the water changes from canary yellow to orange and finally to faint pink. Shut off the acid at this point and again read the level in the burette as closely as possible. When reading the burette take as the level of the liquid the bottom of the slight curve which the surface of the liquid assumes due to the narrowness of the tube.

The analysis of a water sample is usually expressed in parts by weight of impurities per 100,000 parts of water. Thus, when a water is said to contain 20 parts of calcium carbonate what is really meant is that every 100,000 lb. of water contain 20 lb. of this compound.

TEMPORARY HARDNESS

The test with hydrochloric acid as described above indicates the temporary hardness of the water and this is assumed to be caused by the presence of calcium carbonate in the water. To estimate the parts of calcium carbonate per 100,000 multiply the number of cubic centimeters of acid required by 5.

To illustrate, if it took 4.1 c.c. of the one-fifth normal standard-

ized acid solution to neutralize a 200-c.c. sample of water the parts of calcium carbonate per 100,000 parts of water would be taken as

$$4.1 \times 5 = 20.5$$

TEST FOR ACIDITY

If the water to be examined is acidulous the following method must be employed:

Carefully measure out as before 200 c.c. of the water to be tested and add two drops of the phenol-phthalein instead of the methyl orange. Load the burette with the one-fifth normal standardized solution of sodium carbonate and titrate as before, reading off as accurately as possible the number of cubic centimeters required to change the color of the water to a purple-red tint. The number of cubic centimeters thus required is then multiplied by the factor 5 to give the alkali equivalent of the acid present in the water. Thus, if 1.3 c.c. of the sodium carbonate was used in titrating the water contained acid equivalent to a sodium carbonate content of

$$1.3 \times 5 = 6.5 \; parts$$

per 100,000.

PERMANENT HARDNESS

The permanent hardness or hardness due to the sulphates is ascertained by the following test:

Filter a little more than 100 c.c. of the water to be tested and then measure exactly 100 c.c. into a clean vessel and add from the burette exactly 25 c.c. of the standardized sodium-carbonate solution. Evaporate this mixture to dryness in a porcelain dish on the water bath. Next, pour into the dish about 100 c.c. of distilled water, heat gently and stir to insure complete solution of the soluble solid matter in the dish. Next, filter the solution carefully and wash the filter well by pouring warm distilled water into it after the solution has passed through. Collect the filtered solution and the filter washings in the large porcelain basin, add two

drops of methyl orange, titrate with the one-fifth normal standardized hydrochloric acid and read carefully the number of cubic centimeters required to cause the change from canary yellow to faint pink.   The number of cubic centimeters of the acid solution required to bring about the color change is subtracted from 25 and the result multiplied by 5 to give the degrees of permanent hardness, expressed in their equivalent of parts of calcium carbonate per 100,000 parts of water.

Estimating Treatment

It is stated by reliable authorities that water which contains more than 20 parts per 100,000 of impurities, causing permanent and temporary hardness, should be treated before use.   Whether the treatment should be made before the water is fed to the boiler is largely a matter of size of plant or amount of water used.

The quantity of lime required to treat water for temporary hardness (calcium and magnesium carbonates) may be estimated as follows: Pounds of fresh baked lime required per 1000 gal. of water equals number of parts of calcium carbonate in 100,000 (as shown by test for temporary hardness) multiplied by 0.0467.

The pounds of slaked lime required per 1000 gal. of water equals the number of parts of calcium carbonate multiplied by 0.0617.

And the pounds of caustic soda (sodium hydrate) required per 1000 gal. of water equals the number of parts of calcium carbonate multiplied by 0.0667.

Treatment for Sulphates

When lime is used for treating the carbonates the quantity of sodium carbonate or soda ash required to correct the permanent hardness may be estimated as follows: Pounds of soda ash required per 1000 gal. of water equals number of parts solid matter causing permanent hardness, multiplied by 0.0884.

When caustic soda is used for the carbonates not so much soda ash is required for the sulphates for the reason that the caustic soda and the carbonates react chemically to produce sodium car-

bonate (soda ash) which becomes available to react with the sulphates to produce sodium sulphate and calcium and magnesium carbonates (the latter being insoluble).

To estimate the quantity of soda ash required for the sulphates in such a case, proceed as usual to estimate the quantity required as though lime were to be used for the carbonates. Then, subtract from the quantity thus found, $\frac{106}{80}$ times the quantity of caustic soda used for the carbonates.

The foregoing materials for treating water are never 100 per cent. pure when bought in bulk and, consequently, it is necessary to allow for this when making up a treatment. The first step is to find out from the dealer what the percentage of purity is, then divide this percentage into the quantity actually required as estimated above and multiply the result by 100.

TESTING TREATED WATER

It is well to test the treated water occasionally to make sure that the treatment is correctly proportioned. For this purpose the following additional material is needed: About a liter of standardized alcoholic soap solution of such strength that when employing a 200-c.c. sample of water, 1 c.c. of the solution will be equivalent to five parts of calcium carbonate per 100,000 parts of water, also about 2 oz. of a weak solution of silver nitrate.

The test is conducted as follows:

Partly fill an ordinary drinking glass with some of the treated water which it is desired to test. Into this put a few drops of the silver nitrate solution and note whether a snowy precipitate is formed or a brownish color is given to the water. The snowy precipitate is caused by the presence of carbonates and indicates that the quantity of lime should be increased. The brown color indicates an excess of lime.

Next draw a fresh sample of exactly 200 c.c. and pour it into a clean bottle of such size that the sample will not more than half fill it. Put some of the soap solution into the burette and read the quantity as accurately as possible. Next, run a small quantity of the solution into the bottle containing the test sample, shake the

bottle vigorously for a minute or two and note whether a lather is formed.   Continue to add soap solution and shake until a lather is formed which will cover the whole surface of the water when the bottle is lying on its side and remain for five minutes.   When this point is reached, read on the burette scale the number of cubic centimeters of soap solution that was used.   This number multiplied by 5 roughly indicates the total hardness in equivalent parts of calcium carbonate per 100,000 parts of water.

Finally, measure out another fresh sample, exactly 200 c.c. in quantity, and put this into the 22-oz. porcelain dish.   Then, add to the sample two drops of methyl orange and two or three drops of the phenolphthalein.   Titrate with the standardized hydrochloric-acid solution and note the number of cubic centimeters of the solution required to change the red color of the sample to a yellow shade.   Then, run in more of the acid solution and read off the quantity required to turn the yellow to pink.   The first reading multiplied by 10 gives the causticity, while the total cubic centimeters of the acid solution used, multiplied by 5, gives the alkalinity.

If the total hardness, as shown by the soap test, is greater than the alkalinity, it indicates insufficient proportion of soda ash in the treatment.   If the total hardness is less than the alkalinity it indicates a too great proportion of soda ash.   If the alkalinity is greater than the causticity it indicates an insufficient proportion of lime.   If the causticity is greater than the alkalinity it indicates an excess of lime.

The method of estimating from the results obtained from the foregoing tests, what changes to make in the quantities of lime and soda ash, is exactly the same as that employed in making up the original quantities.   To illustrate, if the alkalinity is greater than causticity by 1.5 c.c. of acid or

$$1.5 \times 5 = 7.5 \; parts \; per \; 100,000$$

the weight of the lime supplied per 1000 gal. of water should be increased by

$$7.5 \times 0.0467 = 0.35 \; lb.$$

If it should happen that the causticity was greater than the alkalinity by 1.5 c.c., or 7.5 parts per 100,000, then the weight of the lime supplied should be decreased by 0.35 lb. per 1000 gal. of water treated.

OTHER SCALE REMEDIES

In addition to the staple chemicals dealt with here many other chemicals or preparations have been suggested and tried as scale preventives. Even such ordinary products as potatoes, tanbark, molasses, etc., have had their supporters. In addition, are the many proprietary preparations which have been placed on the market.

Kent's "Mechanical Engineers' Pocketbook" states:

"In cases where water containing large amounts of total solid residue is necessarily used, a heavy petroleum oil, free from tar or wax, which is not acted upon by acids or alkalies, not having sufficient wax in it to cause saponification, and which has a vaporizing point at nearly 600 deg. F., will give the best results in preventing boiler scale. Its action is to form a thin, greasy film over the boiler linings, protecting them largely from the action of acids in the water and greasing the sediment which is formed, thus preventing the formation of scale and keeping the solid residue from the evaporation of the water in such a plastic suspended condition that it can be easily ejected from the boiler by the process of 'blowing off.' If the water is not blown off sufficiently often this sediment forms into a 'putty' that will necessitate cleaning the boilers. Any boiler using bad water should be blown off every 12 hr."

At one time kerosene oil was used somewhat extensively, its action being similar to that of the heavy petroleum oil mentioned in the foregoing paragraph. But the frequency of accidents due to carrying an open flame into boilers in which kerosene had been used caused its use to be largely abandoned.

Recently, graphite has been brought into prominence as a scale preventive and many engineers will testify that it has produced beneficial results. Its action is mechanical rather than chemical.

Fed into the boiler with the water at regular intervals and in stated quantities, it tends to form a coating on the heating surface of the boiler which prevents the scale from adhering. The graphite also intermixes with the crystals of the scale-forming impurities and prevents them from cementing solidly together so that they exist only as a sludge or form of mud which can easily be blown out.

The chapter on feed-water treatment has of necessity dealt with only the most common of the troublesome impurities encountered in water. Water from some sections contains many other impurities which have not been discussed here because of the difficulty of the analysis necessary to detect them. Some of these cause pitting and corrosion and are really dangerous when neglected. In some cases the nature of the water may be such that unless the treatment is very carefully planned and executed the effects produced may be as bad as, or worse than, the effects of the original water.

Taken as a whole the subject of water analysis and treatment is really so complex as to require the study of trained chemical experts. Trying to diagnose and cure feed-water troubles by home methods and remedies is much like trying to diagnose and cure human ills by home treatment. It works well enough when the trouble is simple and slight but in the long run it is often safest and cheapest to consult a good specialist who knows what to look for and how to prescribe and apply the remedy.

CO$_2$ RECORDERS

HOW A CO$_2$ RECORDER WORKS

When you use a sponge to soak up water from the floor you do not consider that anything remarkable has happened. You have seen the tanks at the gas works rise as they filled with gas, and drop down as the gas was discharged, and you thought that a usual proceeding.

The principal reasons why a CO$_2$ recorder records CO$_2$ are really no more mysterious nor remarkable than the absorption of water by a sponge, or the inflation of a tank by gas. Practically, the same physical actions occur in both cases, but the things we use are different.

Because chemicals have unfamiliar names is no reason why we should shy at them any more than we shy at a yeast cake, which is a chemical. Some chemical solutions absorb certain gases just as a sponge absorbs water. You know that to relieve a gas-bound ammonia pump you let the gas discharge into a pail of water. If the gas were discharged into the room the fumes would be quite disagreeable, but when discharged into the water the gas is absorbed like water by a sponge.

Platinum sponge will absorb a surprisingly large amount of hydrogen gas, and the sponge will not increase in volume. To prove that it will absorb this gas we will arrange two bottles, as in Fig. 26. One is filled with water, the other with hydrogen gas. We suspend a piece of platinum sponge in the gas as shown. The sponge will then absorb the gas, create a vacuum in the bottle and draw into it water from the other bottle.

The first experiment showed that some substances do absorb

gas.   We will now experiment with a sample of flue gas of 100 c.c.;
12 per cent. is CO_2 and the other 88 per cent. is made up of
other gases.

We have four bottles, Fig. 27, one containing 100 c.c.(cubic
centimeters) of water; one, 100 c.c. of flue gas; one with a caus-
tic-potash solution and the last bottle we will consider inverted
and full of water.   Opening the pinch cocks on the rubber tubes
connecting the bottles, lift the water bottle to the position indi-
cated by the dotted lines.   The water flows into the second bottle,
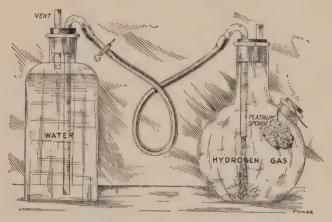
FIG. 26.—Platinum sponge absorbing gas.

forcing the 100 c.c. of flue gas out, causing it to bubble up through
the caustic-potash solution.   After the gas has passed through the
solution, an analysis would show no CO_2, but it would show that
88 c.c. of other gases were present.   At the beginning of the experi-
ment the inverted bottle is filled with water and is sealed by a
little water in the jar, just as the spring-water-bottle drinking
fountains are arranged.   If the flue gas contains 12 per cent.
CO_2 and this bottle is lifted as the gas comes into it, so that the
water levels in the jar and bottle are the same, the water will
run down to the 88 c.c. or per cent. mark and the gas will be at
atmospheric pressure, as it has been throughout the experiment.

100 C.C. FLUE GAS INCLUDING 12% CO₂

CAUSTIC POTASH
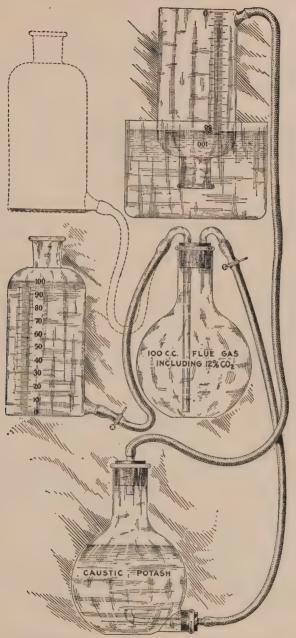
FIG. 27.—Experiment to Show that Caustic-Potash Absorbs CO₂.

The other 12 per cent. of the gas or the CO_2 did not get through the caustic potash.   This experiment demonstrates that a caustic-potash solution absorbs only the CO_2 in the flue gases but allows
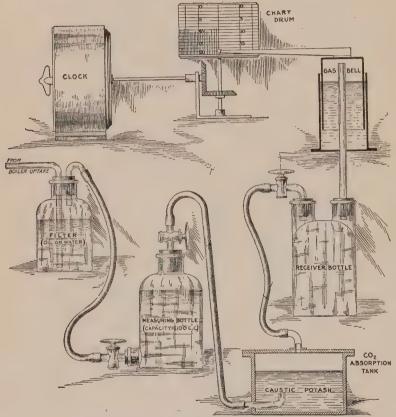
FIG. 28.—The Essentials of a CO_2 Recorder.

the other gases to pass through.   About the same process as that gone through in this last experiment goes on in a CO_2 recorder.

In the recorder the chemical or "sponge" which absorbs the CO_2 is caustic potash.   The pen which marks the chart is attached to

the top of a gas bell that rises and falls as it is filled with and emp-
tied of the CO_2 gas, just as the tanks at the gas works rise and fall.

Before continuing, let us understand why we say such and such
a percentage of CO_2. Percentage means "by the hundred," and
10 per cent. or 12 per cent. means 10 or 12 parts of a total of 100
parts. The total of 100 parts, or 100 per cent., may be any quan-
tity we choose to make it. In measuring CO_2, all or 100 per cent.
of the sample of gas taken from the flue is 100 cubic centimeters
(c.c.), or a little over 6 cu. in. When the flue-gas analysis shows
12 per cent. CO_2 we know that 12 parts, or 12 c.c., of the 100
parts, or 100 c.c., is CO_2 gas.

Fig. 28 shows the essentials of a CO_2 recorder, and when you
understand it, you will understand how and why any CO_2 recorder
works. The gas is brought from the boiler uptake and passed up
through the filter, which contains a bottle nearly filled with oil or
water to take out the soot in the sample. Gas flows into the
measuring bottle, which holds exactly 100 c.c. The sample hav-
ing been measured, it goes to the "sponge," or caustic-potash so-
lution, where all the CO_2 gas is absorbed, and the rest bubbles
through the solution and fills the receiver bottle. From the
receiver bottle the gas is led to the gas bell, which has a water seal
so that gas cannot escape to the atmosphere. This bell and the
pen arm rise and mark the chart against which the pen bears.
When the mark is made the gas goes back through the pipe and
eventually goes to the atmosphere. The chart drum is revolved
by clockwork, as usual.

As the caustic potash absorbs only CO_2 we see that if the meas-
ured sample is high in CO_2, there will be less gas going through the
solution to fill the gas bell, and the pen will not make as long a
mark as when more gas is passing through the solution. On a
recording steam gage or thermometer the pen makes a longer
mark as the pressure or temperature increases from the zero point
on the chart. This is not so with the CO_2 recorder of this sort.
The greater the CO_2 percentage, the shorter the mark.

To get the gas into and out of the measuring and receiving bot-
tles, caustic-potash tanks, gas bell, etc., many siphons and traps

are required.   The motive power for most CO_2 recorders is a stream of water flowing from a pet-cock.   As the stream is increased the machine works faster; that is, it makes a greater number of readings per hour.   With the usual CO_2 machine about seven or eight readings per hour will produce a good chart.

CO_2 RECORDER TROUBLES

The most common of CO_2 recorder troubles is that due to air leaks in the pipe line carrying the flue gas to the recorder.   This line is under a slight vacuum and, unless extreme care is used in "making up" the joints air will get into the pipe and dilute the gas, giving a lower CO_2 reading than is correct.   In cutting the pipe for these lines make the threads large and use new fittings to insure tight joints.   Do not attempt to spring the pipe very much to make up a union as leaks are likely to develop.   Some soot will lodge in the gas line and because of this no ragged edges should be left on the inside of the pipe for these edges tend to hold the soot and cause it to accumulate at these points, reducing the area of the pipe.   It is a good plan to provide the pipe so that a compressed-air hose connection may be made for blowing soot from the pipe.

The water which furnishes the motive power for the recorder is often raised to the supply tank by a motor driven centrifugal pump.   This outfit should get adequate attention as regards cleaning and protection from dust and water.   Because it gives little trouble it is likely to be neglected.

When the water and solution as well as the oil in the filters are changed, clean the containers thoroughly, for dirt will give as much trouble as anything else about a CO_2 recorder.

No definite rule as to interval between renewals of the solution can be given to apply to all machines, but where machines are used steadily day and night and each solution tank holds about three quarts, the solution should be renewed at least every three weeks.   At the end of this time the solution will have absorbed so

much CO_2 gas that its ability to absorb all of that contained in the gas samples admitted to the tank will be greatly impaired and, of course, correct readings will not be made.

Proper Strength of Solution

It is necessary that the caustic potash solution for absorbing the CO_2 be of sufficient strength. A good solution may be had by dissolving one-half pound of commercial caustic potash to a quart of water.

The average fireman is claimed to be a dense individual. "You can't learn him anything" is what is usually said of him. However "thick" he may be, it doesn't take him long to learn how to beat a CO_2 recorder or an average gas sample collector, especially if he is paid a bonus based on the CO_2 percentage he is able to show on the chart.

Where sample collectors are used and where the firemen are practically told that they must produce so and so much CO_2 or find another job, they regard the job as important enough to show good CO_2 results however correctly or honestly the results are obtained.

A favorite trick where sampling cans are used, is to fire any old way until near the time to be relieved. About this time the boiler or boilers served by the can are coaled and conditions made so that a gas high in CO_2 is produced. The can is then quickly filled with water and then quickly emptied, thus drawing into it an instantaneous sample of the gas containing a high percentage of CO_2. Analysis shows a high CO_2 and the fireman is credited with an excellent day's work and some extra pay besides. He invariably "kills" the good thing, however, by getting results that excite suspicion, or by dropping the pressure due to "loafing" of the boilers while he is getting ready to draw the sample. By enclosing the valves and cocks connecting the tank with the water inlet and outlet, in a locked box, this form of deception may be avoided.

It must be admitted that it is better, from an engineering standpoint to have a multiple recorder when CO_2 charts are to be

taken from more than one boiler at one time. With such a machine the chances for successful deception by the firemen are made remote. The objection to the multiple machine or a separate machine for each boiler is the high investment cost, as compared to a single machine piped to all the boilers with cocks to connect the recorder to any desired boiler.

When a single machine is so connected, the "header" to which the lines from all boilers connect with the single pipe leading to the machine, should be boxed and locked, so that the firemen cannot tell by the position of the cocks which boiler the recorder is serving. Even when the cocks are so encased a fireman can so tell to what boiler the machine is connected. He "juggles" each fire separately, covering it carefully and rather heavily, closing the back damper a trifle. Then he observes the readings. The boiler to which special attention has been given will show the results on the chart. When he finds the proper boiler, that one gets the most of his careful attention for the rest of the day.

As nearly every fireman likes to be credited with a good day's work even though he does not get a bonus he will take advantage of these opportunities to make a good showing. For this reason it is best, where financial conditions permit, to install a multiple machine or a single machine for each boiler.

Caring for the Recorder

Any CO_2 recorder is a delicate apparatus and needs the attention of someone competent to care for it without doing more damage than good. This is a point commonly neglected, as one finds many plants in which the firemen, oilers, engineers and, sometimes the cleaners and polishers all jointly take a hand in "gettin' 'er goin'." It is the engineer's duty to look after the recorder and he should do so and also instruct an assistant or one fireman in handling it and then hold him responsible for it, giving everybody else to understand that they are to keep their hands off it.

While the CO_2 recorder is a necessity in any large up-to-date boiler room, like all other recording instruments, the record

from it must be studied and compared and action taken on what they show to be of maximum value.   These machines cost considerable and represent a large investment.   To simply file the charts without studying them would be like putting money in a bank that paid 1 per cent. interest instead of taking advantage of opportunities to get 6 per cent.

CORRECT LOCATION FOR SAMPLE PIPE

It is just as important to locate the gas line in the gas path to insure getting correct samples as it is to have the line air tight. It is quite common to find gas sample pipes so placed in the boiler that the samples being drawn are not truly representative of the quality of the gas passing out of the boiler.   The proper location for the sample pipe in any boiler will be in the center of the gas path and on the boiler side of the damper at the point where the gases leave the boiler.   This does not mean to place the pipe in the center of the opening through which the gases travel as they leave the boiler, but in the center of the gas stream itself.   For example, in a boiler of the B. & W. type the center of the gas stream is usually below the center of the outlet opening.

To be sure to locate the center of the gas stream take several samples from several different places in the stream.   The place at which the composition of the gas varies most widely may be considered as the place to permanently locate the pipe, for above and below and at the extreme sides of the stream the gas velocity is usually less than in the center and "eddies" form.

AIR LEAKS

When it is known that the baffling, doors and brickwork of all the boilers are tight and when different firemen stoke the same boiler at different times and still the CO_2 produced in this particular boiler is lower than in others in the plant, it indicates that the gas line is improperly located or leaks air.   It is important also to make sure that air does not leak in at the point where the pipe enters the settings, although the pipe inside the setting should

be long enough so that a leak here would not seriously effect the reading.

When rubber tubes are used to connect the gas pipe to the recorder or when used to connect different parts of the machine they must be watched for leaks. The recorder is usually located where the room temperature is high and eventually the rubber will harden and crack. Enough tubing should be carried in stock to replace old tubing and avoid taking the recorder out of service. Where parts of the recorder are connected together by small union fittings it should be known that these are tight, when it is found difficult to get such fittings tight, they may be screwed up and soap used to seal the joints until they can be renewed or repaired.

Filter Troubles

In addition to the oil or water filters to take soot from the gas some recorders have other large receptacles filled with cotton through which the gas passes and is cleansed. The filters are usually oil or water sealed to prevent air leaking in. Care must be taken when renewing the waste or whatever medium is used in these filters, to not pack it in so tightly as to prevent the gas going through fast enough. The waste should not be allowed to soak up too much of the liquid used in the seals, for then the flow of gas will be needlessly impeded.

The CO₂ Chart

It is common practice in some plants to neglect putting on the chart the number of the boiler which the chart is serving and also the name of the fireman operating the boiler. This is very poor practice for it is not possible without reference to time sheets to tell what fireman produced a particular chart from some particular boiler. The very purpose of a CO₂ recorder is to act as a check on the fireman but this purpose is defeated if, after the charts are filed away, they cannot tell from which boilers they were taken or who fired that boiler. Never fail to put on the chart the date, boiler number and name of the fireman, and if there is an unusually

low record taken, find the cause and write the particulars on the back of the chart.

With recorders using rectangular charts that are put on a cylindrical drum, care should be taken to get the chart evenly fastened on the drum. Otherwise the zero of the chart will be incorrectly located and the readings will be wrong. The top edge of the chart on most, if not all cylindrical drum machines should be even with the top edge of the drum.

Usually a smeared chart will be produced if more than nine readings are made per hour. About seven readings per hour are sufficient for all practical purposes and this number will give a neat appearing chart. The number of readings are usually regulated by the size of a stream of water running from a pet-cock. It is, therefore important to keep this water free of dirt and particles that might stop the opening in the cock. The water tank should be well covered. This point should be well observed in cement works plants and others where the atmosphere is heavily laden with dust.

PART II

FUEL ECONOMY IN BOILER ROOMS

CHAPTER I

FUELS

Fuels are solid, liquid and gaseous.

Solid fuels embrace coal, wood, peat, lignite, briquetted fuel substances and charcoal, the first four being *natural*, the remaining three, prepared.

Liquid fuels in common use are crude oils, "topped" or partially distilled oils, of which the Mexican fuel oil now so widely used in New England is typical, and tar. The distilled oils, such as gasoline and kerosene are so little used for boilers as to be disregarded in this book.

Gaseous fuels for boiler purposes is confined chiefly to natural gas, though coal gas, producer gas, oil gas and water gas are other well-known kinds.

One frequently hears the term "waste gas," meaning the hot gases from metallurgical furnaces, cement kilns, etc. Boilers that use these gases are called waste heat boilers.

CLASSIFICATION OF COAL

Coal is bituminous (soft), anthracite (hard).

Bituminous may be divided into

Sub-bituminous or black lignite, being between bituminous coal and lignite in texture, color and chemical composition. It is found chiefly in the Western States.

Semi-bituminous coals are those containing more fixed carbon and less volatile matter than the straight bituminous coals, and

less fixed carbon and more volatile than anthracite coal. Semi-bituminous is the most desirable steam coal; New River, Pocahontas, Georges Creek and Windler coals are well-known semi-bituminous grades, and, until the war, were most widely used in New England.

Bituminous may again be classified according to its behavior when burning into free-burning, caking and long flaming:

Free-burning Coal.—The New River, Pocahontas, Georges Creek and others are typical free-burning coals. They are hard and dense, yet splinter easily and burn with a short, usually blue, flame.

Caking Coal.—Some of the Middle-Western coals of Illinois and Indiana are good examples of caking coals. They are high in volatile and hydrocarbon, swell when heated and become pasty at high temperatures, the pieces tending to cake and fuse into a viscous mass. Skill is required to burn these coals, in order to avoid clinker troubles and decrease in the combustion rate owing to the density of the fuel bed.

Long Flaming Coal.—These coals are widely used for gas making. They are high in volatile, and give off a long, yellowish flame. They burn very freely; some long flame coals cake, some are fragile. They are not widely used in boiler furnaces.

Anthracite is very hard, high in fixed carbon, has little or no volatile, does not smoke and is, compared with many bituminous coals, low in ash. The fine grades only, buckwheat, barley, rice and culm or silt, are widely used for steam making.

Semi-anthracite is a name given to hard coal that exhibits some of the characteristics of the bituminous grades, *i.e.*, it is less dense, more fragile and more free-burning than the typical anthracite.

Tables 1, 2 and 3 give the differences between anthracite, bituminous, semi-bituminous and lignite.

Lignite is brown of color and of woody, fiber structure. When freshly mined it is very high in moisture, as high as 50 per cent. When exposed to the air it disintegrates when the moisture dries out of it. Lignite is briquetted and in this form lends itself to boiler furnaces, though progress is being made in using it unpre-

TABLE 1.—DIFFERENCES IN CONSTITUENTS OF COALS
(Fixed carbon and volatile taken as 100 per cent.)

Coal	Fixed carbon, per cent.	Volatile, per cent.	Heating value per lb. of combustible
Anthracite...................	97 to 93	3 to 7	14,600
Semi-bituminous..............	88 to 75	12 to 25	15,000 to 16,000
Bituminous, Eastern...........	75 to 60	25 to 40	14,500 to 15,500
Bituminous, Western...........	68 to 50	32 to 50	13,000 to 14,500
Lignite......................	50 on down	50 on up	10,000 to 13,500

pared with stokers. When lignite is carbonized, *i.e.*, when the moisture and most of the volatile are driven off, the lignite is quite solid and does not break up in pieces or flakes as easily as when merely air-dried. When carbonized it burns very well on the ordinary grate and on stokers. To burn natural lignite successfully requires furnaces of large volume.

Table 3 gives the composition of some typical anthracite and bituminous coals and lignite.

Cannel coal is used almost solely for gas making and is characterized by its high volatile content, usually over 35 per cent.

Table 2 gives the composition and heating values of common woods and wood refuse.

TABLE 2.—COMPOSITION AND HEATING VALUE OF WOOD AND WOOD REFUSE

Wood	Per cent.				B.t.u. per lb.
	Carbon	Hydrogen	Oxygen	Ash	
Ash.................	49.18	6.27	43.91	0.57	8,480
Beech..............	49.06	6.11	44.17	0.57	8,590
Elm................	48.89	6.20	44.25	0.50	8,500
Oak................	50.16	6.02	43.36	0.37	8,320
Fir.................	50.36	5.92	43.39	0.28	9,050
Pine...............	50.31	6.20	43.08	0.37	9,150
Wood charcoal.......	75.5	2.5	12.0	1.0	10,800 to 12,600

TABLE 3.—ANALYSES OF TYPICAL AMERICAN COALS
Chiefly from Bulletins of the Bureau of Mines

Coal and location of mines	Fixed carbon, per cent.	Moisture, per cent.	Volatile, per cent.	Ash, per cent.	Sulphur, per cent.	B.t.u. per lb., dry
Anthracite						
PENNSYLVANIA						
Lackawanna........	87.74	2.12	3.91	6.35	0.12	15,200
Lehigh Valley.......	76.00	1.00	7.00	16.00	......	12,500
Wilkesbarre.........	76.94	1.34	6.42	15.30	......	11,900
Scranton...........	84.46	0.97	5.37	9.20	......	12,300
Wharton...........	86.40	3.04	3.95	9.88	0.46	15,000
Lycoming Creek.....	71.53	0.67	13.84	14.00	......	13,300
Bernice.............	89.39	0.97	8.56	9.34	1.04	15,500
MARYLAND...........	83.60	......	16.40	......	......	11,200
ARKANSAS (semi-an-thracite)..........	74.06	1.35	14.93	9.66	......	14,000
ALABAMA						
Bibb County........	59.56	3.16	31.05	6.23	1.20	14,141
Bibb County........	52.09	6.43	28.56	12.92	1.08	12,395
Bibb County........	65.74	......	34.26	......	1.33	15,604
Blount County......	65.28	2.93	29.06	2.73	0.65	14,693
Jefferson County....	60.96	2.88	25.98	10.18	0.94	
Jefferson County....	56.91	2.88	29.56	10.65	2.04	13,459
Jefferson County....	67.16	2.81	26.52	3.51	0.59	14,643
Jefferson County....	57.95	......	26.12	15.93	3.21	
Shelby County......	61.56	2.21	31.45	4.78	0.63	
Tuscatoosa County .	68.55	1.60	24.98	4.87	0.51	14,697
Walker County.....	53.01	2.25	35.70	9.04	1.09	13,133
ARKANSAS						
Franklin County....	79.35	3.77	13.96	2.92	0.74	
Johnson County.....	76.91	1.37	14.76	6.95	1.52	14,330
Ouachita County....	37.31	......	41.90	20.79	0.88	9,714
Sebastian County...	72.66	3.21	14.84	9.29	3.12	13,588
COLORADO						
Adams County......	43.60	19.65	30.75	6.00	0.33	8,638
Boulder County.....	49.74	......	42.89	7.37	0.68	12,472
Boulder County.....	46.98	21.63	27.84	3.55	0.37	9,508
Delta County.......	52.16	3.29	39.74	4.81	0.62	13,379
El Paso County.....	27.27	34.40	24.44	13.89	0.14	6,055
El Paso County.....	49.92	......	41.68	......	0.68	14,207
Garfield County.....	55.29	3.81	36.30	4.60	0.40	13,410
Garfield County.....	52.0	10.7	31.5	5.8	0.40	11,690

TABLE 3.—*Continued*

Coal and location of mines	Fixed carbon, per cent.	Moisture, per cent.	Volatile, per cent.	Ash, per cent.	Sulphur, per cent.	B.t.u. per lb., dry
Gunnison County...	90.60	......	3.41	5.99	0.82	14,490
Gunnison County...	56.16	2.98	33.62	7.24	0.40	13,428
Jefferson County....	39.47	23.52	34.09	7.42	0.80	8,426
Los Animas County.	67.12	......	32.88	......	0.81	15,563
Mesa County.......	55.34	......	39.07	5.59	1.44	13,577
ILLINOIS						
Clinton County.....	44.29	11.64	35.41	8.66	3.41	11,290
Franklin County....	53.97	......	37.06	8.97	1.80	13,243
Logan County......	39.75	14.77	32.90	12.31	3.01	10,406
La Salle County.....	38.56	13.87	37.26	10.31	3.44	10,985
La Salle County.....	53.12	......	46.88	......	4.98	14,486
Madison County....	39.98	11.87	36.57	11.58	4.75	10,768
Madison County....	53.46	......	46.54	......	4.88	14,272
Marion County.....	39.79	10.25	37.43	12.53	3.70	11,077
Montgomery County	42.44	14.89	34.80	7.87	3.61	11,016
Montgomery County	53.77	......	46.23	......	6.02	14,155
St. Clair County....	37.05	9.88	42.26	10.81	3.83	11,439
Williamson County .	53.10	......	36.80	10.10	3.08	13,084
Saline County.......	52.20	7.51	32.81	7.48	1.58	12,686
Sangamon County...	40.36	14.29	37.17	8.18	4.41	11,007
INDIANA						
Clay County........	46.08	15.38	32.66	5.88	1.95	11,680
Davies County......	45.90	10.95	35.47	7.68	3.73	......
Greene County......	45.38	13.53	33.54	7.55	0.95	11,768
Knox County.......	44.45	13.70	35.94	5.91	2.66	11,930
Pike County........	46.27	12.88	34.71	6.14	1.70	11,801
Pike County........	53.14	......	46.86	......	3.77	14,567
Sullivan County.....	47.01	14.23	33.04	5.72	0.89	11,722
Sullivan County.....	55.42	......	44.58	......	4.49	14,594
Vigo County........	43.65	9.55	36.19	10.61	3.72	11,759
Warwick County....	41.22	9.62	36.14	13.02	4.43	11,122
IOWA						
Appanoose County..	40.36	17.13	35.44	7.07	4.00	10,931
Lucas County.......	51.38	......	39.11	7.73	2.94	10,505
KANSAS						
Cherokee County....	46.85	2.01	35.99	15.15	5.27	13,000

TABLE 3.—*Continued*

Coal and location of mines	Fixed carbon, per cent.	Moisture, per cent.	Volatile, per cent.	Ash, per cent.	Sulphur, per cent.	B.t.u. per lb., dry
KENTUCKY						
Bell County........	57.55	2.91	36.01	3.53	0.89	14,322
Hopkins County....	46.64	9.10	36.21	8.05	2.97	
Johnson County.....	54.13	6.43	36.20	3.24	1.17	13,455
Pike County........	61.73	......	31.17	7.10	0.58	14,177
MARYLAND						
Allegany County.....	75.00	2.3	14.5	8.2	1.10	14,020
Allegany County....	80.34	19.66	......	......	1.82	15,700
MICHIGAN						
Saginaw County	53.55	11.55	31.65	3.25	0.95	12,442
MISSOURI						
Adiar County.......	39.45	14.59	32.05	13.91	3.69	10,260
Macon County......	38.95	14.74	38.95	7.78	3.79	11,185
MONTANA						
Cascade County.....	52.24	9.58	23.24	14.95	2.00	9,932
Cascade County.....	51.44	7.49	27.29	13.78	2.32	11,007
Chouteau County...	34.61	22.84	29.31	13.24	0.80	7,898
Gallatin County.....	73.22	2.05	16.45	8.31	0.86	14,092
Sweet Grass County.	36.68	25.26	23.51	14.55	0.41	6,383
NEW MEXICO						
Colfax County......	50.75	2.19	35.95	11.11	0.57	13,063
M'Kinkley County..	44.58	14.49	37.08	3.85	0.41	11,468
NORTH DAKOTA						
Billings County.....	28.53	34.50	29.76	7.21	0.99	6,714
Ward County.......	22.64	36.64	30.74	9.98	0.45	6,394
OHIO						
Belmont County....	47.18	4.14	39.30	9.38	3.96	12,874
Hocking County....	53.41	9.72	32.44	4.43	0.54	12,247
Jefferson County....	49.90	3.53	37.45	9.12	3.47	13,072
OKLAHOMA						
Coal County........	45.68	7.07	36.41	10.84	3.64	11,468
La Flore County....	58.89	3.13	31.72	6.26	0.86	14,022
Pittsburgh County..	54.88	3.55	34.01	7.56	1.22	13,583
OREGON	35.44	18.96	28.50	17.10	0.54	7,769

TABLE 3.—*Continued*

Coal and location of mines	Fixed carbon, per cent.	Moisture, per cent.	Volatile, per cent.	Ash, per cent.	Sulphur, per cent.	B.t.u. per lb., dry
PENNSYLVANIA						
Allegheny County ..	56.84	3.67	34.03	5.46	1.37	13,874
Cambria County....	72.4	3.2	18.50	5.87	1.27	14,320
Cambria County....	66.8	4.1	23.0	6.1	1.91	14,000
Indiana County.....	55.99	4.35	27.76	11.90	1.51	12,964
Somerset County....	72.14	2.10	18.00	7.76	0.60	14,220
Somerset County....	76.76	0.59	16.61	6.04	0.91	14,753
Somerset County....	69.87	2.64	16.54	10.95	1.94	13,488
Washington County.	55.83	1.70	37.20	5.27	1.13	14,435
Westmoreland County...........	58.11	2.01	33.56	6.32	1.32	14,152
Sullivan County.....	75.58	3.40	9.34	11.68	0.81	13,120
RHODE ISLAND						
Newport County....	64.43	16.80	2.30	16.47	0.59	9,230
Providence County..	78.69	4.54	3.01	13.76	0.87	11,624
Providence County..	59.67	4.51	3.46	33.32	0.13	8,809
TENNESSEE						
Anderson County....	54.51	3.25	35.63	6.61	0.85	13,514
Campbell County ..	53.03	5.38	35.54	7.05	0.99	13,089
TEXAS						
Houston County....	19.56	32.50	37.02	10.84	0.56	7,500
UTAH						
Carbon County.....	45.45	6.13	40.07	8.35	0.56	12,217
Carbon County.....	28.34	3.20	64.31	4.15	0.35	
Iron County........	46.21	12.56	36.43	4.80	5.24	10,942
VIRGINIA						
Lee County.........	51.77	5.69	34.43	8.11	2.31	13,117
Russel County......	55.03	2.28	35.69	7.00	0.66	13,936
Tazewell County (Pocahontas)......	74.43	4.50	17.52	3.55	0.80	14,656
WASHINGTON						
King County........	40.97	4.93	33.01	21.08	0.54	10,733
King County........	48.48	4.77	34.33	12.42	1.12	12,204
King County........	49.0	7.4	39.5	4.1	1.28	12,500
Lewis County.......	28.11	27.17	33.80	10.92	0.33	7,569
Lewis County.......	51.68	4.08	26.93	17.31	1.26	11,860
Pierce County.......	52.83	2.74	36.31	8.12*	0.49	13,538

TABLE 3.—*Continued*

Coal and location of mines	Fixed carbon, per cent.	Moisture, per cent.	Volatile, per cent.	Ash, per cent.	Sulphur, per cent.	B.t.u. per lb., dry
WEST VIRGINIA						

The names of the mines are given for the West Virginia Coals as these will identify the coals more readily than the names of the county in which the mines are located.

Coal and location of mines	Fixed carbon, per cent.	Moisture, per cent.	Volatile, per cent.	Ash, per cent.	Sulphur, per cent.	B.t.u. per lb., dry
Alaska..............	75.24	3.07	16.83	4.86	0.50	14,519
Ballinger...........	68.1	3.5	22.5	5.9	0.60	14,170
Boone..............	71.02	3.32	23.28	2.38	0.76	
Belva..............	49.86	1.8	44.9	3.44	0.87	15,330
Carlisle............	75.70	3.72	18.83	1.74	0.56	14,884
Carlisle............	73.81	2.94	19.25	4.0	1.34	14,578
Claremont..........	73.28	3.54	17.03	6.15	0.51	14,099
Derryhale..........	75.68	3.33	17.34	3.65	0.83	14,593
Dunglen............	74.83	3.23	19.32	2.63	0.75	14,785
Dunloop...........	77.17	2.68	16.81	3.34	0.48	14,670
East Sewell........	73.18	3.34	21.25	2.23	0.56	14,821
Edmond...........	72.2	3.5	21.0	3.25	0.56	14,550
Elmo..............	70.0	2.9	23.5	3.6	0.65	
Fayette............	72.21	2.46	22.21	3.12	0.60	14,756
Gentry (Layland) ...	76.74	3.01	15.32	4.93	0.80	14,500
Glen Jean..........	75.2	3.7	16.0	5.1	1.15	14,310
Glen Jean (Nichol)..	74.83	2.77	18.87	3.53	0.64	14,735
Harvey.............	74.77	2.94	19.97	2.32	0.57	14,751
Hawkes Nest (Mill Creek)...........	67.2	5.0	24.5	3.3	0.55	14,280
Laurel Creek........	75.5	3.7	16.0	4.8	0.50	14,370
Lawton (Greenwood Mine)...........	72.86	4.17	16.56	6.41	0.68	14,069
Lookout............	71.4	3.4	24.0	2.2	0.50	14,680
Macdonald.........	72.71	3.26	21.57	2.46	0.78	14,773
Macdonald (Sugar Creek)...........	72.8	4.4	18.5	4.3	0.70	14,300
Minden............	77.24	2.95	17.12	2.69	0.54	14,816
Page...............	61.33	2.39	31.72	4.56	1.66	14,819
Powellton..........	59.85	1.98	34.41	3.76	0.85	14,739
Price Hill..........	75.53	2.58	19.01	2.88	0.90	14,877
Prudence..........	71.79	3.85	19.40	4.96	0.63	14,240
Redstar............	73.20	5.24	16.84	4.72	0.86	14,112

TABLE 3.—*Continued*

Coal and location of mines	Fixed carbon, per cent.	Moisture, per cent.	Volatile, per cent.	Ash, per cent.	Sulphur, per cent.	B.t.u. per lb., dry
Robins.............	77.5	2.8	15.0	4.7	0.65	14,550
Rush Run..........	71.68	2.10	22.67	3.55	0.75	14,900
Scarbro............	74.31	4.19	17.83	3.67	0.66	14,398
South Caperton.....	73.25	3.35	21.25	2.15	0.55	14,738
South Nuttal.......	72.0	3.4	22.0	2.6	0.50	14,730
Stone Cliff.........	73.48	2.63	17.81	6.24	0.47	14,281
Stuart.............	72.71	3.78	21.20	2.31	0.52	14,702
Sun Sun...........	72.59	2.12	21.74	3.55	0.90	14,915
Thayer............	73.42	3.6	16.83	6.15	0.67	14,216
Thurmond.........	73.69	3.35	18.65	4.31	0.51	14,827
Turkey Knob.......	74.82	3.22	19.22	2.74	0.77	14,816
Whipple...........	72.8	2.7	20.5	4.0	0.60	14,600
Winona...........	71.16	3.22	23.53	2.09	0.57	14,780
Clarksburg (Pitcairn)	48.40	1.98	40.54	9.08	4.20	13,466
Acme (Keystone)....	59.60	2.66	33.30	4.44	1.14	14,368
Charleston (Black Band)............	53.16	4.21	35.41	7.22	0.64	13,379
Monarch...........	54.56	3.25	34.61	7.58	1.22	13,523
Winifrede..........	55.20	3.57	36.28	4.86	1.32	13,948
Holden............	57.86	1.60	33.70	6.84	1.27	13,918
Algoma (Pocahontas)	77.48	2.87	12.94	6.71	0.62	
Arlington (Pocahontas)	78.6	2.9	14.0	4.7	0.45	14,600
Ashland (Pocahontas)...............	76.01	4.2	14.0	5.7	0.45	14,143
Bear Wallow (Pocahontas)...........	79.3	3.0	13.5	4.19	0.47	14,620
Big Sandy..........	78.6	3.0	14.5	3.9	0.70	14,770
Coalwood..........	75.25	2.19	13.91	8.65	0.57	13,995
Crumpler (Pocahontas)..........	77.7	3.5	14.5	4.31	0.51	14,580
Davy..............	78.9	3.7	13.5	3.85	0.60	14,620
Eckman (Pulaski)...	76.35	3.32	16.22	4.11	0.55	14,587
Elkhorn(Pocahontas)	79.00	3.24	13.13	4.63	0.49	14,598
Elk Ridge (Pocahontas)...........	79.28	3.10	13.38	4.24	0.53	14,600
Ennis (Turkey Gap)	74.69	3.67	15.09	6.55	0.46	14,290
Gilliam (Pocahontas)	77.57	3.38	13.36	5.69	0.49	14,332
Huger.............	79.5	2.8	13.5	4.22	0.58	14,700
Jed Jed............	79.8	2.8	11.5	5.9	0.82	14,410

TABLE 3.—*Continued*

Coal and location of mines	Fixed carbon, per cent.	Moisture, per cent.	Volatile, per cent.	Ash, per cent.	Sulphur, per cent.	B.t.u. per lb., dry
Keystone (Pocahontas)...........	78.5	2.8	13.5	5.33	0.62	14,510
Kyle (Lynchburg mine)............	78.2	3.3	14.0	4.52	0.54	14,600
Landgraff..........	80.27	3.06	12.81	3.86	0.55	14,695
McDowell.........	77.5	3.28	15.06	4.16	0.45	14,548
Maybeury.........	76.6	3.97	15.78	3.65	0.59	14,605
Norfolk...........	76.13	3.59	15.02	5.26	0.39	14,267
Powhatan.........	79.77	2.76	13.05	4.42	0.60	14,749
Roderfield.........	74.60	2.00	17.50	5.90	0.55	14,590
Switchback........	77.3	4.1	14.5	4.1	0.52	14,510
Twin Branch.......	77.0	3.4	16.0	3.59	0.69	14,750
West Vivian........	79.2	1.9	14.0	4.90	0.55	14,710
Goodwill..........	77.8	2.9	15.5	3.80	0.55	14,730
Simmons..........	79.4	3.5	14.0	3.10	0.85	14,740
Springton.........	79.75	3.24	12.31	4.70	0.59	14,530
Wenonah..........	79.10	3.58	13.17	4.15	0.56	14,598
Widemouth........	75.49	3.37	15.65	5.49	0.54	14,371
Elk Garden........	72.55	1.29	14.77	11.39	1.53	13,634
Oakmont..........	73.87	0.82	16.10	9.21	1.10	14,103
Wabash...........	71.91	1.99	17.72	8.38	1.11	14,112
Bretz.............	61.29	2.26	28.71	7.74	0.85	13,999
Beckley...........	75.6	4.5	17.5	2.4	0.80	14,650
Cranberry..........	77.16	4.40	16.15	2.29	0.49	14,764
Lanark...........	77.12	3.15	16.71	3.02	0.68	14,873
Price Hill.........	73.75	3.83	17.88	4.54	1.32	14,432
Raleigh...........	79.40	3.20	14.00	3.40	0.73	14,740
Slab Fork.........	79.88	2.81	13.77	3.54	0.54	14,765
Stanaford.........	78.93	3.68	15.10	2.29	0.55	14,818
Stonewall.........	77.19	3.04	17.24	2.53	0.72	14,854
Thomas...........	70.04	2.39	22.39	5.18	0.67	14,557
WYOMING (mine)						
Kirby.............	48.09	16.11	32.96	2.84	0.50	11,211
Fort Steele........	50.99	8.85	36.58	3.58	0.92	12,062
Hauna............	44.87	11.96	36.93	6.24	0.37	10,638
Iron..............	44.86	15.46	36.16	3.52	0.79	10,517
Hamilton..........	34.08	28.39	31.05	6.48	0.72	7,997
Superior...........	51.10	10.23	34.11	4.56	1.28	12,028

TABLE 4.—MOISTURE AND HEATING VALUE OF SAW MILL REFUSE

Kind of wood	Refuse	Moisture, per cent.	B.t.u. per lb., dry
Mexican White Pine.........	Sawdust and hog chips	51.90	9,020
Yosemite Sugar Pine.........	Sawdust and hog chips	62.85	9,010
Redwood...................	Sawdust and hog chips	52.98	9,040
Fir, Hemlock, Spruce and Cedar....................	Sawdust	42.06	8,949

TABLE 5.—COMPOSITION AND HEATING VALUE OF BAGASSE

Source	Moisture	Carbon	Hydro-gen	Oxygen	Nitro-gen	Ash	B.t.u. per lb., dry
				—Per cent.—			
Cuba............	51.50	43.15	6.00	47.95	....	2.90	7,985
Porto Rico.......	41.60	44.28	6.66	47.10	0.41	1.35	8,359
Louisiana........	52.10	......	....	......	....	2.27	8,370
Java............	......	46.03	6.56	45.55	0.18	1.68	8,681

Tables 4 and 5 are from tables in " Steam," Babcock & Wilcox Co.

Fuel Oil.—The heating value of fuel oil varies from 16,000 to 20,000, with 18,000 and 19,000 being fair averages.

TABLE 6.—HEATING VALUES OF FUEL OILS

	Specific gravity	Degrees Bé.	B.t.u. per lb.	Specific heat*
California (Bakersfield).	0.992	....	17,117	0.398
Texas (Beaumont).....	0.924	....	19,060	
Pennsylvania..........	0.886	....	19,200	0.500
Mexico...............	0.981	....	17,600	

* The higher the hydrogen content the higher the specific heat.

TABLE 7.—COMPOSITION, WEIGHT AND VAPORIZING POINTS
OF FUEL OILS

	Fuel oil	California crude	Mexican crude
Carbon, per cent.................	84.35	81.52	83.83
Hydrogen, per cent..............	11.33	11.01	12.19
Oxygen, per cent.................	2.82	....	0.43
Nitrogen, per cent...............	0.60	6.92	1.72
Sulphur, per cent................	0.90	0.55	2.83
Gravity, deg. Baumé.............	26 to 28	12 to 36	12 to 23
Pounds per gal..................	7.3	7.6	7.8
Vaporizing temp. F..............	130	230	175

Flash point, deg. F. (closed cup) Mexican fuel oil............	178
Fire point, deg. F. (open cup) Mexican fuel oil..............	262

Water Gas Tar.—This is not widely used for boiler fuel; it weighs $9\frac{1}{2}$ lb. per gal., has a heating value of 16,800 B.t.u. per lb. and ordinarily will evaporate 13.5 to 14 lb. water per pound.

Waste (Heat) Gases.—In recent years considerable progress has been made in the utilization of waste gases from open-hearth and blast furnaces, brick, cement and other kilns. The average entering gas temperature for open-hearth furnaces is from 900 to 1400 deg. F., and for cement kilns 1200 to 1500 deg. F.; the gases from copper furnace often is as high as 2200 deg. F. for long periods. Ordinarily, with clean boilers the heat transmission from gas to boiler per square foot per degree difference per hour is from 4 to 5 B.t.u. for open-hearth furnaces; 3 to 6 B.t.u. for cement kilns; 2 to 6 for copper furnaces, and 2 to 7 for beehive coke ovens.

In all waste heat utilization in boilers the great cause of loss of heat—and capacity—is air leakage. It is not uncommon to raise the CO_2 100 per cent. by stopping air leaks in the flue between the furnace or source of gas and the boiler.

The boilers should be dusted at least four times per day— every 6 hr.

Natural Gas.—This fuel varies considerably in composition.

TABLE 8.—ANALYSES OF NATURAL GAS

Source	Per cent.				B.t.u. per cu. ft. at 60 deg. F.
	Marsh gas	Ethane	Oxygen	Nitrogen	
West Virginia......	81.05	17.40	1.00	0.55	1,030
West Virginia......	83.20	15.55	0.10	0.50	1,020
West Virginia......	83.50	15.5	0.00	0.30	1,026
....	82.00	13.2	0.40	0.80	1,090

Besides the above there are small amounts of carbonic oxide, carbonic acid, and illuminants.

The cubic feet of gas per horsepower-hour varies from 40 to 80, depending upon type of boiler setting, but chiefly influenced by the excess air supplied. Excess of air is not necessarily too great when the flame is blue; but the author prefers a white flame when the load demand is heavy.

CHAPTER II

COMBUSTION OF COAL IN BOILER FURNACES

The combustion of coal, particularly bituminous coal, as it occurs in a boiler furnace, is a very complex chemical performance. The man who operates boilers, who is the man for whom this book is intended, is urged not to worry himself about the chemistry of combustion. In the following pages the author attempts to set forth the most important things that the engineer should know about combustion as he must control it in boiler furnaces.

The power-plant engineer should possess and study Bureau of Mines Technical Paper No. 137 and Bureau of Mines Bulletin No. 135, which are, in the author's opinion, the most valuable publications dealing with the combustion of coal in boiler furnaces.

Temperature of Distillation of Coal.—The foregoing has to do particularly with bituminous coal. All of the serious problems that arise in the burning of bituminous coal are due almost solely to the volatile matter in the coal. This volatile is made up of heavy oils and tar, which, on the application of sufficient heat are given off in the form of liquids and vapors, the vapors becoming gas on absorbing heat as they arise from the fuel bed. The temperature in a boiler furnace may be all the way from 2000 deg. F. in a hand-fired boiler, to 3200 deg. in a stoker-fired boiler. The volatiles in the coal begin to be driven off at about 300 deg. and for most coals the heaviest volatiles are driven off at 900 deg.

Rapidity of Combustion.—When the liquids and vapors are converted into a gas they form the combustible gases which must receive sufficient air to burn them most completely or to the highest CO_2 percentage compatible with furnace efficiency. The highest CO_2 does not always indicate that the highest furnace efficiency is being obtained. This is particularly true with highly
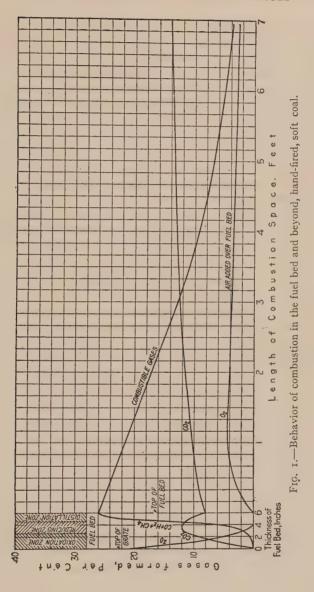
volatile coals, but the mixture of air admitted to the fuel bed and above it with the combustible gases should be thorough and complete before the gases have left the combustion chamber.   There must be a chemical union of the atoms of the air and the atoms of the combustible gases.   In the ordinary boiler setting it requires roughly a second for the gases to leave the fuel bed and reach a point in the boiler furnace which is at a temperature too low to support combustion.   This shows that the thorough mixture of air and combustible gases must take place in an astoundingly short time.

Mixture of Air and Combustible Gases.—Air coming through a fuel bed gives off some of its oxygen to the combustible gases that have formed in the fuel bed and to the gases arising from the burning of the carbon in the coal.   The balance of the air coming through the fuel bed rises in streams from the bed and tends to create layers of gas and layers of air in the boiler furnace.   This, of course, does not bring about the thorough mixing of air with the combustible gases necessary to complete the combustion of the latter.   Perhaps a good way to visualize the entry of air through a fuel bed and into the combustion space is to imagine the air rising in vertical columns while alongside of each column of air is a vertical column of combustible gas.   One can readily see that if these columns of air and gas were to pass on unbroken and unmixed through the combustion chamber and boiler to the stack, complete combustion would not take place, the furnace efficiency would be low and the fuel loss great.   The air, of course, does not rise in straight vertical columns, neither does the combustible gas.   The streams of air and gas in passing through the fuel bed are buffeted about because of the irregular shapes of the air passages through the fuel bed, caused by the differences in the size and shape of the fuel on the grate.   This action greatly assists the mixture of air and combustible gases so vital to complete combustion.   If the boiler is provided with arches, baffles, or wing walls in the furnace there is further mixture of air and combustible gases as both pass on their way out of the combustion chamber and into the boiler proper.

Influence of Character of Fuel Bed.—From the foregoing it is plain that if there is large clinker on the grate, or if there are holes in the fire, or if the pieces of coal on the grate are of extremely varying sizes, or if the fuel bed is uneven, 6 in. in one place and 12 in. in another, there will not be that thorough mixing of air and combustible gases which must be had if coal is to be used economically. From the foregoing it is plain also that if the boiler setting leaks great quantities of air from the boiler room, which air is say at 70 deg. F., while the gases in the furnace are from 2000 to 3200 deg., that this air which leaks in will cool the combustible gases and air in the furnace, and which came through the fuel bed, thus tending to lower the temperature below the point where combustion is well supported.

Once the reader thoroughly appreciates the importance of the preceding paragraphs he will then be able to discover almost any reason for inefficient combustion or waste of fuel in the boiler furnace while combustion is going on.

Combustion in the Fuel Bed.—Referring now to Technical Paper No. 137, already mentioned, the curves, Fig. 1, are from this bulletin, and if studied carefully will tell the engineer more about what takes place in a fuel bed during combustion than whole pages of text can tell him. Notice that the CO_2, or carbon dioxide, reaches a maximum 4 in. from the grate in a 6-in. fuel bed, there being presumably no ash on the grate. Then, as the surface of the fuel bed is reached the CO_2 gives up some of its oxygen and is reduced to CO. This happens because there is little or no oxygen at this point—in a solid fire—other than that contained in the CO_2 which gives up some of its oxygen and is reduced from about 15 per cent. at 4 in. from the bottom of the fuel bed to 10 per cent. at the surface of the fuel bed. When the free oxygen that came in with the air under the grate is all used up the CO_2 acts as an oxidizing agent and by its contact with the hot coals is reduced to CO. The rate of reduction depends upon the temperature of the fuel bed. The higher the temperature the faster the CO_2 is reduced to CO. The percentage of CO_2 that is reduced to CO at any given temperature depends to a

Fig. 1.—Behavior of combustion in the fuel bed and beyond, hand-fired, soft coal.

certain limit on the length of time that the CO_2 is in contact with the hot carbon.   The longer the contact the larger the percentage of CO_2 reduced to CO.   The limit of reduction is the equilibrium between the CO_2 and CO and carbon at the temperature existing in the fuel bed.   Beyond this limit the percentage of CO_2 does not change, no matter how long the time of contact.   A study of the chart will reveal that the ordinary fuel bed really acts as a gas producer in that all of the free oxygen is used up by the combustible gases before the surface of the fuel bed is reached, therefore producing a very considerable amount of combustible gas, which, if it is to continue to burn and produce heat, must have more oxygen.   The reader should have in mind, however, that the furnace in which the tests were made did not have any air leaks above the fuel bed, nor holes in the fire, and no air was admitted through any opening above the fuel bed.   The fuel was broken into pieces of uniform size, which is a condition that does not exist in practice.   As stated above, the fuel bed in most types of furnaces acts primarily as a gas producer.

At the surface of the fuel bed the gases contain no oxygen, only 6 to 8 per cent. of carbon dioxide, and 20 to 32 per cent. of combustible gases.   The composition of the gases is practically independent of the rate of air supplied.   The larger the quantity of air forced through the fuel bed the greater the rate at which the fuel burns or gasifies, but the ratio between the weight of air supplied and the weight of fuel burned remains constant at about 7 to 1.   Further study of the chart shows that when the supply of air through the fuel bed is shut off by clinker or ash on the grate, the combustion of the fixed carbon stops.   If under such conditions the coal is spread into the furnaces with undiminished rate, only the volatile matter is distilled off and burned in the combustion space with the air supplied over the fuel bed, or with the air that may get through holes in the fire or leak in through the boiler setting, while the fixed carbon accumulates on the fuel bed, rapidly increasing its thickness.

Where Clinker Forms.—It is important also to notice that the temperature of the fuel bed is highest where the CO_2 in the

fuel bed is highest.   A little reflection will show that this means
that should the heat produced at this point be unable to get away
or should the ash in the coal melt at a very low temperature,
comparatively, fusion of the ash will occur in the upper regions
of the layer of ash and will tend to run down through the ash,
fuse and plug up the air openings in the grate.   More than this
happens, for on its way to the grate it passes into the oxidizing
zone, where it cools and tends to solidify, forming the clinkers so
troublesome in boiler operation.   The zone is called reducing,
because in it the CO_2 is being reduced to CO.

Distillation of Volatile on the Stoker.—The superiority of the
stoker over-hand firing is due in no small measure to the fact that
the volatile in the green coal as it comes on to the stoker is driven
off slowly, and in most stokers at a point where large quantities
of air come through the fuel bed to mingle with the volatile
gases.

Secondary Combustion.—When the combustible gases do not
receive enough air for their combustion when the gases are over
the grate or at points in the combustion chamber near the fire,
combustion of these gases sometimes occurs further toward the
up-take or boiler damper, at which place they receive sufficient
air for their combustion, either by the air coming through leaks
in the boiler setting or through the presence of air which may have
come up through the grate, but was stratified and therefore not
mixed with the combustible gases until mingled with them at
the point where secondary combustion occurred.   If the tempera-
ture is low, as it frequently is toward the rear of the boiler, secon-
dary combustion will not take place.   The temperature at which
secondary combustion will not take place is rather difficult to
state, for it depends upon the composition of the combustible
gases; but it is likely that it does not occur in a temperature under
1000 to 1500 deg.

Burning of Soot in Boiler Furnaces.—As pointed out before,
the volatile matter in heated coal contains tar, saturated and
unsaturated hydrocarbons, carbon monoxide (CO), and hydrogen.
These must be burned in the space above the fuel bed where

the high temperature favors the formation of simple compounds so that the final products to be burned are largely tar, CO and H_2. In the absence of sufficient oxygen for the complete combustion of these compounds the hydrocarbons are quickly decomposed by the high temperature into soot, hydrogen and the carbon monoxide All of these hydrocarbons in any form disappear or are burned at a distance of 1 to 2 ft. from the surface of the fuel bed during the ordinary operation of the furnace. Soot is formed at the surface of the fuel bed by heating the hydrocarbons in the absence of air (oxygen). The reader is asked to read this sentence again that he may understand that the soot is not formed by the hydrocarbon gases condensing on the surfaces of the boiler, which are, of course, much cooler than the flame temperature.

Quantity of Tar and Soot at Surface of Fuel Bed.—The combustible matter rising from the fuel bed is roughly 12 per cent. in the form of tar and soot. Immediately at the surface of the fuel bed the quantity of tar is large, but decreases rapidly as the gases pass through the combustion space.

CO With High CO_2.—In general an increase in the rate of combustion and in the excess of air is accompanied by a decrease in the quantity of soot and particularly in the quantity of tar. This decrease in the quantity of tar and increase in the quantity of soot seems to indicate that the volatile matter leaves the fuel bed as heavy hydrocarbon mostly in the form of tar and that the tar is decomposed by the high furnace temperature and absence of oxygen into soot. The process of decomposition of the hydrocarbons is complicated by the presence of the CO_2 which reacts with soot and combustible gases and is itself reduced to CO. The foregoing is a clear explanation of why CO persists in furnace gases and why one is likely to find it with high or with low percentages of CO_2.

The length of time in which the tars are decomposed into soot and gases is very short. At the rate of combustion of 30 lb. per sq. ft. of grate per hour the gases travel with a velocity of about 10 ft. per sec. (In the boiler under discussion.) As most of the tars disappear during the first foot of the gas travel from

the fuel bed, the time taken for the decomposition of the tar is about $\frac{1}{10}$ sec. This high rate of decomposition is undoubtedly due to the high temperature near the fuel bed, which is between 2700 and 3000 deg., ordinarily.

Soot Difficult to Burn.—After the soot has been formed it is most difficult to burn it in the atmosphere of the furnace for the reason that ordinarily the furnace atmosphere is very low (in weight) in oxygen. The reason for the slow combustion of soot in highly diluted oxygen probably lies in its complex molecular structure. It is commonly supposed that a molecule of soot consists of a considerable number of atoms and that a similarly large number of molecules of oxygen is required to come in contact with the molecule of soot before the latter can combine with the oxygen. The chances of the molecule of soot finding this large number of molecules of oxygen in the furnace gases are small, therefore the slow combustion. Thus, assuming the molecule of soot to consist of 12 atoms as represented by the symbols CH_{12}, there will be required 12 molecules of oxygen to burn the one of soot. The reaction for the combustion of the soot may be expressed by the formula

$$CH_{12} - 12O_2 = 12CO_2$$

For comparison, the reaction for the combustion of CO is given in the following equation:

$$2CO = O_2 + 2CO_2$$

It is easy to understand that the 2 molecules of CO can find 1 molecule of oxygen in the furnace gases much more quickly than 1 molecule of soot can find 12 molecules of oxygen. This explains why a simple gas like CO and hydrogen burn very much more readily in the furnace than does the soot. It is possible that if sufficient oxygen could be got to the hydrocarbons and the oxygen adequately mixed with these hydrocarbons that they would burn directly to products of complete combustion, that is, to CO_2 and to H_2O without decomposing and forming soot. This again shows one of the chief reasons why the stoker is superior

to hand firing, namely, that in nearly all stokers air finds its way up through the green coal coming on the stoker and which is being slowly heated in the presence of air (oxygen), this taking place before the coal, the volatile of which is being driven off, gets in or about the high temperature zones of the fuel bed.

Effect of Moisture on Combustion.—Those who have tried to burn fuels exceedingly high in moisture, as are some of the Texas and North Dakota lignites, have found it impossible to do so in ordinary furnaces, hand or stoker fired, without first allowing the moisture to dry off, or without first carbonizing the fuel. Similar trouble is experienced in the burning of slack, which often is high in moisture. To evaporate the moisture requires that heat be absorbed by the water, or moisture, and this in turn decreases the temperature in the active zone of the fuel beds, perhaps directly as the moisture contents, that is, the higher the moisture in the coal the more the temperature reduction of the active zone of the fuel bed. This heat absorption from the active zone of the fuel bed may be so great as to put out the fire. This happens in the burning of some lignites, the surface of the fuel bed being almost black, while beneath this layer of slow burning coal may be a very active and high temperature zone. To correct this condition the moisture must be evaporated from the fuel, either before it is put into the furnace at all, or evaporated before the green coal can get far enough into the furnace or on to the grate to come upon the active, or high temperature part of the fuel bed. This may be done by directing the flame toward the front of the boiler where the green coal is coming into the furnace. See the chapter on Boiler Settings, pages 227 and 228.

Commercial Maximum CO_2 with Different Fuels.—No end of confusion has been caused in the minds of power-plant operators by the wide publication of tables which purport to show the fuel losses and the excess air for various percentages of CO_2, usually from 0 to 15 per cent. These tables are always, so far as the writer knows, based on pure carbon. They should be used only as rough guides. The fixed carbon and volatile hydrocarbons in fuels vary most widely, and because fuels thus vary widely

in composition, the gas analyses widely differ. The best CO_2 to carry with a given coal in a given furnace will even vary a little for widely different combustion rates.

Considered by itself the CO_2 merely indicates the weight ratio of air to fuel. Hydrogen very greatly influences the highest possible percentage of CO_2 attainable with a particular fuel. The more hydrogen the fuel contains the less will be the CO_2 in the gases from the fuel. The point is that a certain percentage CO_2 with one fuel may indicate excellent combustion while the same percentage for another fuel would indicate poor combustion. For example: burning nautral gas, high in hydrogen, 8 per cent. CO_2 indicates very good practice, while 12 per cent. from a coal containing but 4 or 5 per cent. hydrogen would indicate combustion which is far from the best obtainable in practice.

The percentage of CO_2 in the products of perfect combustion of various coals have been determined and are given herewith:

	Per cent. CO_2
Anthracite culm.................................	19.5
Semi-anthracite................................	19.0
Semi-bituminous................................	18.8
Bituminous, coking.............................	18.8
Bituminous, non-coking.........................	18.7
Sub-bituminous (Wyoming)......................	18.9
Lignite..	19.2
Bagasse will give, in commercial boiler operation...	12.0
Fuel oil will give............................	13 to 15.0

CHAPTER III

BOILER SETTINGS

More fuel is wasted because of wrongly designed boiler settings and settings wholly unsuited to the fuel than many are aware of even in these days of enlightenment. Roughly one-half of the coal fed to a stoker or shoveled on a grate must be burned in the combustion space of the furnace; the other half is burned to gas in the fuel bed itself. The gases rising from the fuel bed are, in most boilers, only a fraction of a second in passing from the fuel bed to the parts of the boiler or furnace which are at a temperature too low to support combustion; say, 1000 deg. F.

While traveling through this distance at such speed, the globules of tar in the gases must absorb heat, vaporize into gas, and this gas (methane, CH_4) as well as the CO and the soot, which forms at the surface of the fuel bed—all must unite thoroughly with the oxygen in the air admitted for combustion in this short time. This clearly tells why low boiler settings, whether hand or stoker fired cannot be operated smokelessly and economically however skilled the fireman may be. The more highly volatile the coal and the higher the rate of combustion the worse does the condition become.

CHIEF FUNCTIONS OF A BOILER SETTING

A boiler setting with its grate or stoker and its dampers, doors, steam jets or other air injection devices should perform the following functions.

1. It should develop many times the normal horsepower of the boiler.

2. It should be of volume sufficient to give the combustible gases time to properly and adequately mix with the air admitted for combustion.

3. It should, in some cases, be provided with wing walls, arches, baffles or restricted passages to assist in mixing the combustible gases and air.

4. It should have refractory arches, particularly a coking arch, immediately above the green coal coming into the furnace. The combustible gases should be inclosed in space surrounded, except at the gas outlet, by fire-brick at high temperature until combustion of the gases is practically complete.

Besides these the setting should withstand the temperature changes met in operation without cracking or bulging; it should be maintained air-tight.

RATIO OF FURNACE VOLUME TO GRATE AREA

Boiler furnaces until very recent years at least never were designed with thought that some ratio of furnace volume to grate area and combustion rate was essential to economy. Experience of recent years has shown that this ratio is vital to economy and successful combustion. There was little need for economizing on fuel; high combustion rates were uncommon, therefore there was no reason to study the action of gases in a boiler furnace. The volume of combustion space to grate area is too small in nearly all except recent installations, soft coal, high in volatile considered as the fuel used.

Table 9 gives the combustion space-grate area ratio in some actual installations.

TABLE 9.—RATIO COMBUSTION VOLUME TO GRATE AREA

Boiler	Combustion space, cu. ft.	Grate area, sq. ft.	Ratio combustion volume to grate area
Heine.................	250	35.0	7.14
Babcock & Wilcox*.....	318	87.4	3.64
Locomotive type........	160	30.0	5.34
Stirling type, Normand..	78	58.6	2.34

*BABCOCK & WILCOX: Using blast-furnace gas, 2 cu. ft. per rated horsepower (very great volume); Oil-burning water-tube boilers, 60 to 80 cu. ft. per burner of 350 lb. of oil per hour capacity.

The experiments of Kreisinger, Augustine and Ovitz, Bureau of Mines Bulletin No. 135, showed more clearly than anything else has shown that different coals require different size furnaces or volume of combustion space. The higher the volatile in the coal the more volume is required, combustion rate and excess air being the same. For example, for given conditions of combustion rate and air excess Pittsburgh coal requires about 20 per cent. more combustion volume, and Illinois coal about 40 per cent. more, than Pocahontas. The volatile in each is: Pocahontas 18.05 per cent., Pittsburgh, 35 per cent., and Illinois, 46.5 per cent.

The size of the combustion space does not increase in direct proportion as the volatile in the coal. Just how it does increase is not known, though when the combustion rate of a given coal is doubled and the quantity of volatile distilled off is doubled per unit of time with the same air excess and completeness of combustion, the combustion space need be increased only 20 per cent.

Table 10 is of value in showing the influence of furnace volume upon combustion. It is from Bureau of Mines Bulletin No. 135.

TABLE 10.—SIZE OF COMBUSTION SPACE REQUIRED FOR THREE COALS

Completeness of combustion, per cent. of undeveloped heat	Combustion rate, lb. per sq. ft. per hr.	Excess of air, per cent.	Cubic feet combustion space per sq. ft. of grate		
			Pocahontas	Pittsburgh	Illinois
5.0	50	50	2.7	2.9	4.3
3.0	50	50	3.2	3.7	5.3
2.0	50	50	3.6	4.4	6.3
1.0	50	50	4.0	5.6	8.9
0.5	50	50	4.8	6.8	11.9
5.0	25	50	2.0	2.2	3.5
3.0	25	50	2.3	2.7	4.35
2.0	25	50	2.7	3.1	5.1
1.0	25	50	3.4	4.0	6.2
0.5	25	50	4.0	5.0	7.1

In whatever part of the country the boiler may be located, whatever kind of coal (bituminous) may usually be supplied or

whatever the usual combustion rate or load on the boiler, it is well to provide a high setting. The extra cost is little and is recovered in a matter of weeks. Table 11 is suggested as a general guide. In recent B. & W. type boiler installations using multiple retort underfeed stokers one finds 10 cu. ft. of furnace volume per square foot of active grate area.

TABLE 11.—HEIGHT OF BOILER SETTINGS

(Dimensions in inches)

Furnace or stoker	Horizontal tubular (Shell to dead plate)	Boiler water-tube	
		Horizontal baffles	Vertical baffles
		(Bottom of front headers to floor)	
Hand fired:			
(Same for "Hand Stokers")..	48 to 54	72 to 96	78 to 96
Chicago No. 8..............	36 (Bottom of shell to floor)	72	*
Chain grate[1]...............	90	90 to 120	120 to 144
Side-feed, full extension furnace	84	96	120
Front-feed[2].................	96	96	120 to 144
Underfeed:			
Type E...................	66	72	84
Jones...................	66	72	72 to 84
Mollock..................	66	72	72
Taylor...................	72	84	120 to 168
Westinghouse.............	72	84	120 to 168
Riley....................	72	84	120 to 168
Fuel oil and tar burning.....	72	84	96 to 120

[1] Extension furnace desirable.
[2] A long coking arch is desirable.

Hand-fired Smokeless Setting.—Fig. 2 shows the Chicago setting, one which has done much to abate smoke and produce fuel economy in the Middle-West. Dimensions are given. For horizontal tubular boilers allow 36 in., shell to dead plate; for water-tube, vertical baffles, 72 in., bottom of front header to floor.

Figs. 3 to 14 show boiler settings of design suitable for coals

SPECIFICATIONS FOR IMPROVED SETTING HORIZONTAL TUBULAR BOILERS SET AS IN FIG. 2

Diameter shell	84"	84"	78"	78"	72"	72"	66"	66"	60"	60"	54"	54"
Length shell	20'	18'	20'	18'	16'	16'	18'	16'	18'	16'	16'	14'
C	42"	42"	42"	42"	36"	36"	36"	36"	36"	36"	36"	36"
D	2'2"	6'	2'	6'	2'	2'	2'	2'	2'	2'	2'	1'10"
E	6'6"	6'	6'	6'	5'6"	5'6"	5'6"	5'6"	5'	5'	4'6"	4'6"
F	7'	6'	6'8"	6'6"	2'6"	2'6"	2'4"	2'4"	2'2"	2'	2'	2'
G	2'10"	2'10"	2'8"	2'8"	2'8"	1'8"	1'7"	1'7"	1'6"	1'5"	1'5"	1'5"
H	1'10"	1'10"	2'9"	2'9"	5'6½"	5'6½"	5'7"	5'	5'4"	4'11"	4'11"	4'8"
I	6'4"	6½"	5'5½"	5'10½"	1'7"	1'7"	5'3¼"	5'3½"	5'	4'4½"	4'½"	2'
J	6½"	6"	1'6"	6"	1'10½"	1'10½"	1'10½"	1'9"	5'6½"	4'7½"	1'7½"	1'6"
K	5'6"	5'10½"	1'6"	2'3"	2'4"	2'4"	1'8"	1'5½"	1'6½"	1'½"	1'6"	1'6"
L	1'10½"	2'	2'3"	2'10"	1'6"	2'6"	2'4"	2'4"	2'2"	2'	2'	2'
M	2'3"	2'3"	1'6"	2'3"	1'1½"	1'1½"	1'3½"	1'1½"	2'1½"	1'8½"	1'8½"	1'8½"
N	3'	3'	1'6"	1'6"	2'	1'8"	1'3¾"	1'1½"	1'1½"	1'11½"	1'11"	2'
O	1'6"	1'6"	2'6"	2'6"	2'5"	5'1¼"	2'2¼"	1'1¾"	1'11½"	1'11½"	1'8½"	2'
P	2'9"	2'9"	5'5½"	5'5½"	1'1"	1'1½"	3'½"	1'11"	1'11½"	1'11"	1'8½"	1'2½"
Q	1'4"	1'4"	5'5½"	5'5½"	1'1½"	2'8"	3'8½"	3'4½"	3'5½"	3'2"	3'2"	1'9"
R	5'5½"	3'3½"	4'2¾"	3'11"	3'2"	3'1"	1'9"	3'9"	3'9"	5'6"	9"	1'10"
S	4'2"	2'2"	2'3"	2'11"	9"	2'	3'8½"	1'9"	2'	9"	9"	9"
T	2'2"	2'	9"	2"	1'	9"	9"	9"	9"	9"	9"	9"
U	1'	1'	9"	9"	1'	1'	9"	9"	9"	10"	10"	1'½"
V	1'1½"	1'1½"	1'1½"	1'2"	1'1½"	1'1¾"	11"	11"	1'1¾"	1'1¾"	1'1½"	1'1½"
Number and size of tubes	92–4"	92–4"	88–4"	88–4"	70–4"	70–4"	54–4"	54–4"	46–4"	46–4"	36–4"	36–4"
Heating surface in tubes	1932.0	1738.8	1842.8	1658.5	1323.0	1176.0	1017.7	904.6	866.9	770.6	604.8	529.2
Heating surface in shell	219.9	197.9	204.2	183.8	169.6	150.7	155.5	138.2	141.3	125.6	113.1	99.0
Total heating surface tubes and shell, sq. ft.	2151.9	1936.7	2047.0	1842.6	1492.6	1326.0	1173.2	1042.9	1008.2	896.2	717.9	628.2
Boiler horsepower	215	194	205	184	149	133	117	104	101	90	72	63
Square feet of grate surface	45.5	42.0	42.25	39.0	36.0	33.0	30.25	27.5	27.5	25.0	20.25	18.0
Area through each bridge wall retort, sq. in.	820.0	756.0	761.0	702.0	648.0	594.0	544.5	495.0	495.0	450.0	364.5	324.0
Area between bridge wall and deflection arch, sq. in.	2448.0	2448.0	2040.0	2040.0	1770.0	1770.0	1484.0	1484.0	1326.0	1326.0	984.0	984.0
Area under deflection arch	3280.0	3024.0	3041.0	2808.0	2592.0	2376.0	2177.0	1979.0	1800.0	1979.0	1457.0	1296.0
Area of tubes, sq. in.	1011.0	1011.0	967.0	967.0	769.0	769.0	593.0	593.0	505.0	505.0	396.0	396.0
25% over flue area	1264.0	1264.0	1208.0	1208.0	961.0	961.0	741.0	741.0	631.0	631.0	495.0	495.0

Notes.—First grade of fire-brick to be used throughout with the exception of the combustion chamber floor and the side walls of the chamber back from a point 1 ft. behind the rear face of the deflection arch. Fire-doors MUST provide for special air admission of an area equal to 4 sq. in. for each square foot of grate surface, when working pressure on boiler is 20 lb. or less. If desired, these doors may be used on boilers carrying more than 20 lb. pressure. Make the effective area through damper frame not less than the combined area of tubes. See ordinates for breeching and other regulations. Table applies only for the ordinary conditions and is subject to revision or modification for unusual conditions. Heating surfaces are in square feet, areas in square inches, except for grate surface.

F = Width of Grate

G = Tube Sheet to Wall

Steam Jets
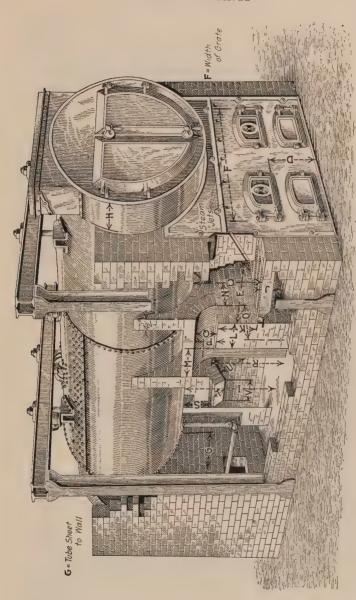
Fig. 2.—Chicago setting. Table gives dimensions.
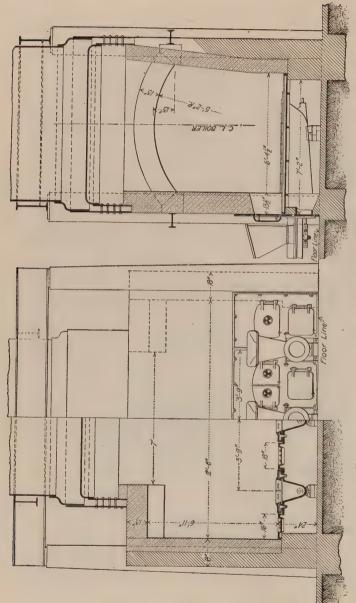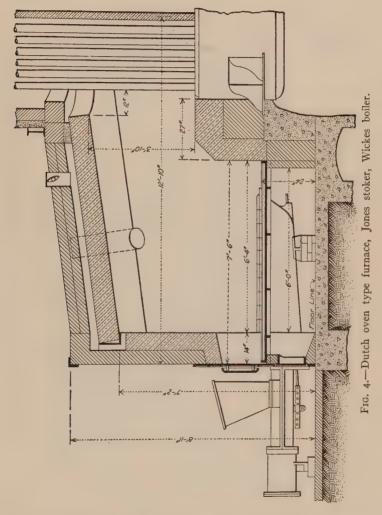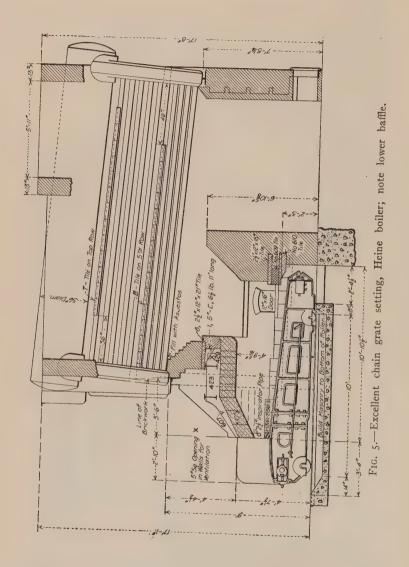
Fig. 3.—Roomy setting for Jones stokers under Manning boilers.

ranging in volatile from 12 per cent. (Pocahontas) to 40 per cent. (Illinois coal).

FIG. 4.—Dutch oven type furnace, Jones stoker, Wickes boiler.

For burning slack coal or lignites both of which are high in moisture, the slack running about 15 to 20 per cent. and lignite

Fig. 5.—Excellent chain grate setting, Heine boiler; note lower baffle.
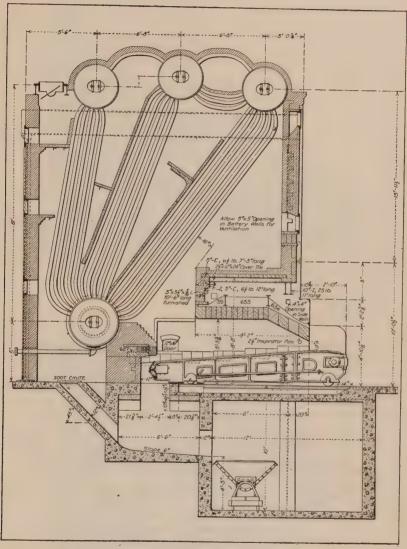
FIG. 6.—Stirling boiler, chain grate, stoker setting.
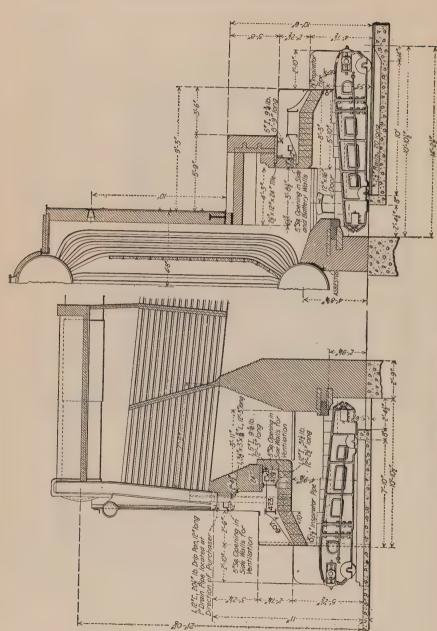
FIG. 7.—Chain grate settings, Edge-Moor and Erie City boilers.
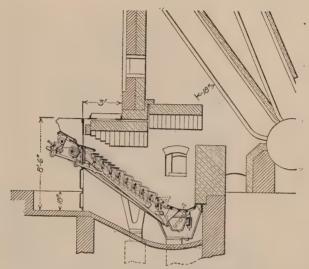
Fig. 8.—Roney stoker with secondary arch.
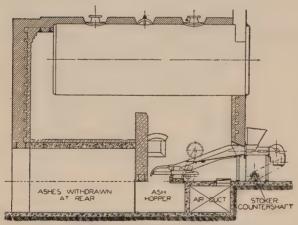
Fig. 9.—Underfeed stoker H R. T. boiler.
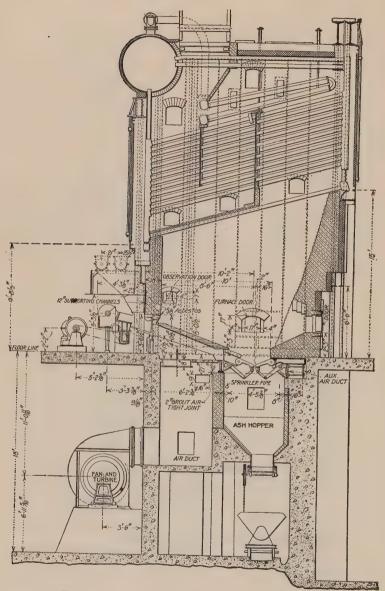
FIG. 10.—Westinghouse stoker; cross drum boiler.
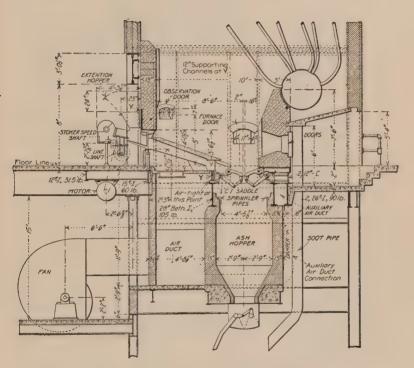
FIG. 11.—Excellent setting, Sterling boiler.
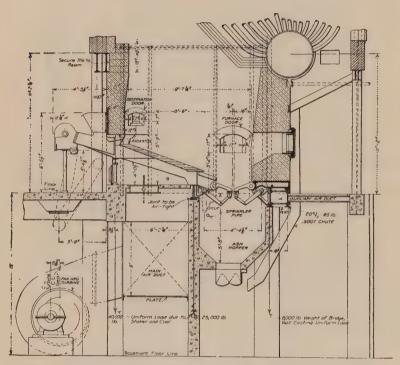
FIG. 12.—Setting for burning lignite; note large combustion volume.
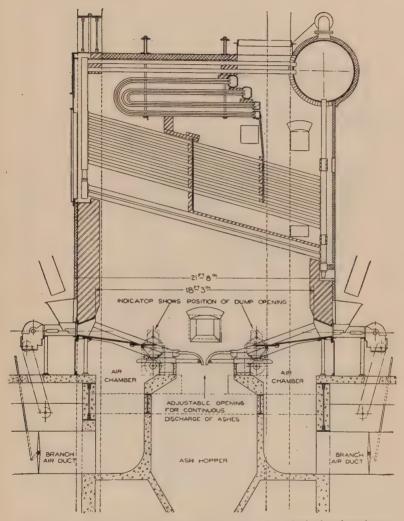
FIG. 13.—Setting for B. & W. cross-down boiler with underfeed stokers front and rear.
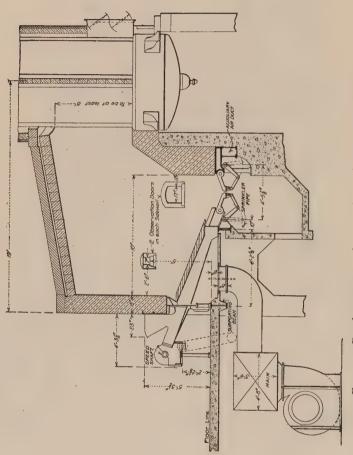
Fig. 14.—Dutch oven type furnaces for various vertical boilers.
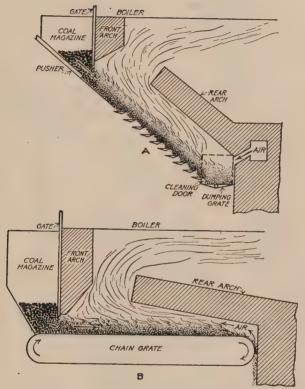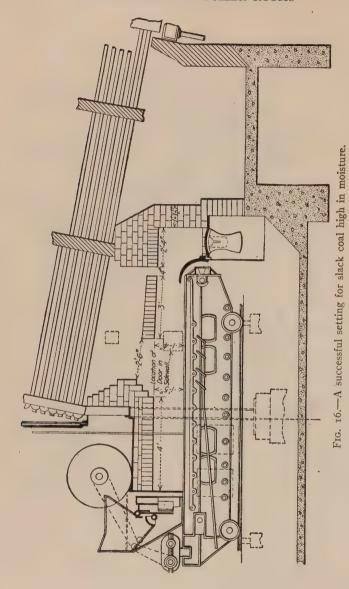
FIG. 15.—*A*, Step grate; *B*, chain grate, with rear arches, for lignite.

FIG. 16.—A successful setting for slack coal high in moisture.

25 to 40 per cent., a furnace of the general design of Fig. 15 is well suited. It directs the flame forward over the green coal, evaporating much of the moisture as the coal comes into the furnace. Fig. 16 shows a furnace designed by J. F. McCall of Calgary, Can., for burning Drumheller slack, averaging 15 per cent. moisture, 42.47 per cent. fixed carbon, 29.9 per cent. volatile, 12.18 per cent. ash, 11,450 B.t.u.; 335 per cent. builders' rating of the boiler was developed. The fire was kept 4 in. thick and the CO_2 averaged 11.3 per cent. Coal of 22 per cent. moisture is successfully burned in this setting.

CHAPTER IV

HAND FIRING SOFT COAL

No person can learn to fire a boiler by reading about it. He must do it. The following is intended to tell him how it should be done with bituminous coal of the high and low volatile grades.

Starting the Fire.—Cover the entire grate with 3 in. of green coal spread evenly (see Fig. 17). Dry wood or shavings are then spread on top of the coal and on these here and there over the surface is put oil-soaked shavings or waste. Ignite by throwing
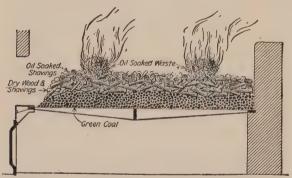
Fig. 17.—Starting fire, soft coal hand-fired furnace.

burning waste in the center of the grate. Put on the blower lightly at first or open the damper and ashpit doors if no blower is used; increase the draft as necessary, throwing on more coal, a little at a time, until the fire is going satisfactorily.

If lumpy gas coal is available spread it on the grate first before starting the fire and put the coal ordinarily used on top of it, then the shavings; this prevents the small coal falling through the grate.

The fire burns from the top down, the volatile passing through the hot zone, becoming well vaporized so that it mixes well with the air supplied for combustion.

Maintaining the Fire.—Maintaining the fire between cleaning periods requires no mean skill. The coking method with which every fireman who reads should be familiar is not always the best. A glance at Fig. 18 shows that only a small part of the total surface of the green coals coking is exposed to the direct heat of the furnace. If the pile of coal coking could be left there long enough, the volatile would be driven off so slowly as to make no objectionable smoke. But it must soon be pushed and spread over the
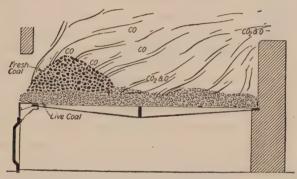
Fig. 18.—Coking coal, hand-firing.

hot fire, and when this is done the volatile in the coal beneath the surface of the pile has reached a temperature where only a slight increase is needed to make it give forth its vapors so suddenly as to not give time for adequate mixing with air, thus making dense black smoke. The lowered furnace temperature also helps to make smoke at this time. All this is clear when we realize that the rapidity of distillation depends, for any given temperature, upon the surface of coal exposed to the heat. Less smoke will be made, even with a "puffy" coal if the coal is shoveled on in small piles until most of the volatile is driven off before the piles are leveled, and if steam-air jets or other means of getting air in over the fire are used.

The alternate method of covering has the same disadvantage, in that the green coal, even though thrown on but one-half or one-third of the fuel bed, has so much of its surface exposed at once to the incandescent coal that distillation is more rapid than can be cared for by the heat of the furnace.   Theoretically the method is good, but it is hard work for the fireman and unfortunately gets him into the habit of disturbing the fuel bed with rake or slice bar, a most egregious fault.

Whether the coking, alternate, or the divided method of covering is used, or if the whole fire surface is covered at once, the covering must be thin and done frequently.   This is particularly true of caking coals.   Caking coals form the surface crust so peculiar to them during the coking process.   The crust prevents sufficient air reaching the coal, and high spots form in the fuel bed.   If these places are covered with fresh coal before the surface of the high spots have been broken and allowed to burn away, the trouble grows worse.   Do not cover unburned places in the fuel bed.   The troubles had with many caking coals may be made nearly negligible if the fire is always covered lightly and often. Use the rake and slice bar as little as possible, but remember that the crust of caking coal must be often broken, if formed, to maintain the desired steam pressure.   When breaking the crust, be careful not to so disturb the fuel bed as to get ashes on or near the top of the fire.   Usually this causes serious clinker trouble, which stops the normal flow of air through the fuel bed and gives rise to more caking.

For a not too-heavy covering and at normal hand-firing combustion rates, it takes from 2 to 6 min. for the volatile to be driven off.   During the major part of this time use the steam jet if provided or open the fire-door to admit air in above the fire.   The time it should be left open depends, of course, upon the rapidity of distillation and the quantity of the vapor and gas distilled.

From the smoke standpoint the difficult time to prevent smoke is during the cleaning period.   First be sure that there is sufficient live coal when cleaning begins.

There is probably no more common way of cleaning a fire than

that shown in Figs. 19, 20 and 21. The back half of the grate is
first cleaned as shown in Fig. 19, then about 3 in. of green coal
is thrown on the bare grate and all the live coal pushed back on
top of the green coal, which begins to burn from the top down,
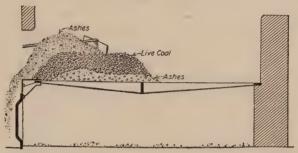
FIG. 19.—Common method of cleaning fire, stationary grate.

making it necessary for the vapors and gases to pass through the
hot coal (see Fig. 20). The ashes are pulled from the front of the
grate, green coal thrown on and the live coals at the back pulled
forward and evenly distributed over the whole fuel-bed surface,
Fig. 21.
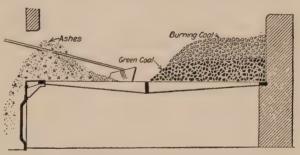
FIG. 20.—Cleaning front half of stationary grate.

When men are being taught to fire the author believes it best
to teach them to clean one side, half of the grate at a time, by wing-
ing the live coals over with the bar in the usual way. There is
less danger of serious clinker troubles by this method as unless

one is quite skilled, he is almost sure to get ashes or clinker mixed with the live coals, melting the ash or clinker. Ordinarily a clinker gets harder every time it is melted after it has solidified.

Shaking grates are, of course, preferable to stationary grates; then the above methods of cleaning do not apply.
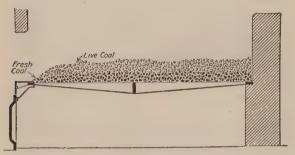
FIG. 21.—Cleaned fire, live coal on top of green coal.

SOME POINTS ABOUT FIRING

Carry a fire not more than 8 to 12 in. thick. Cover the fire only where it burns out. Break the surface of the fuel bed if it cakes over. Never disturb the fire with the slice bar when it is not necessary to do so. Coke the coal on the dead plate. If steam jets for air injection over the fire or for draft are used, keep the tips free of dirt and scale.

Regulate the fire for the most part by operating the up-take damper at the back of the boiler.

Never entirely close the ashpit doors (natural draft) while there is a heavy and hot fire on the grates. Slow down the combustion rate by closing off the back damper—never tightly closed. The dampers should be installed so that they cannot be tightly closed.

If large clinkers form clear away the coal so they may be pulled out of the furnace without being dragged over the live coals, otherwise pieces of clinker left on the coals will melt and fuse again becoming increasingly difficult to handle.

Become familiar with the systems of damper, draft and feed-water control. This cannot be done better than by using the makers' catalogs and observing the operation and construction of the systems. A book alone will not tell you much.

Firing Fine Anthracite Waste.—Anthracite waste usually contains up to 35 per cent. or more of incombustible. The grades of fine anthracite are Buckwheat numbers 1, 2, 3, 4 and 5. No. 4 goes through $\frac{1}{8}$ in. round mesh and over $\frac{1}{16}$ in. round mesh; No. 5 goes through $\frac{1}{16}$ in. round mesh. Nos. 3 and 4 are good fuels when burned on the Coxe stoker; No 5 is too fine for any stoker now marketed. Best results are had with fine anthracite, either stoker or hand-fired, when mixed with bituminous coal. The soft acts as a binder and increases the heating value for a given volume of fuel; it also is useful for building bottoms in the fire and for filling holes. The amount of bituminous to mix with the anthracite varies from 5 to 10 per cent. depending chiefly on the size of the anthracite. The smaller the coal particles the greater the quantity of bituminous required, until with straight No. 4 80 per cent., 20 per cent. bituminous should be used. Usually no bituminous is used with No. 1 buckwheat.

Mixtures of anthracite and bituminous coals cannot be successfully burned unless the mixture is thorough as the coal goes on to the grate. Mix it at the boilers with shovels if possible and do not transport it before it is shoveled into the furnace.

Thickness of Fire.—Carry as thin a fire as possible without blowing holes in it. Use every precaution to have a good bottom to the fire when finished cleaning it; say a bottom 3 to 5 in. thick. Use straight soft coal for bottoms if necessary, taking the soft coal from floor bins on the boiler-room floor.

Draft.—The draft will vary with the conditions of the fuel bed and the combustion rate required to carry the load—from 2 in. to 7 in. water gage.

Soot.—Large quantities of soot and flue ashes are formed, increasing with the combustion rate; it may amount to 10 per cent. by weight of the coal fired, and may have on analysis, a higher B.t.u. value than the coal itself. The soot is most difficult

to burn however high its heating value as shown by analysis.   The ash will frequently fuse on or in the boiler tubes, and sometimes its removal is difficult.

Considerable experience is required for the fireman to successfully burn these mixtures without leveling fires every 8 to 20 min. with a bar.   This is, on the whole, bad practice.   He must be experienced to prevent too great loss of combustible to the ashpit.   If one contemplates burning such mixtures all the time, the writer is of the opinion that a stoker of the Coxe type is essential, if losses and labor difficulties are to be avoided.

BURNING FUEL OIL UNDER BOILERS

Fuel oil finds an ever increasing use as fuel for steam boilers. At this writing, in the midst of the most severe conditions of rail and marine transportation, fuel oil is displacing 1,000,000 tons of coal per year in New England alone.

For analyses and properties of fuel oils see the chapter on Fuels, page 197.

For boilers it will likely be but a few years when none but the heavy oils, 16 deg. Bé. to 10 deg. Bé will be available. Mexican oil is typical of these heavy oils.

The oil is heated, then atomized so it will mix well with the air for combustion. Steam and mechanical methods of atomization are in common use; air atomization also is used. Steam atomization is most widely favored for stationary boilers. Ordinarily the oil is stored in tanks and there heated so it will readily flow or to about 115 deg. F.; it then passes through strainers of brass wire netting of about 40-to-the-inch mesh or its equivalent, then pumped to the burner where it is atomized. But just before it gets to the burner it is further heated to 15 to 20 deg. above its vaporization temperature. The oil pumping outfit usually has its own little storage and heating tank.

Unless familiar with burning oil get a thorough appreciation of the importance of thorough atomization of the oil, for upon it depends, other conditions right, the thoroughness of mixture with the air supplied for combustion. This mixture is more easily obtained than with high volatile (20 to 45 per cent.) coals; but it must be obtained and maintained. The operator must be very careful, much more careful than when burning coal, to avoid too much excess air. But do not try for a too high CO_2 without at the same time keeping the furnace temperature below 2800 to 3000 deg. F., otherwise the fire-brick may melt away.

With the same furnace, the higher the combustion rate the more difficult it is to get the best mixture of atomized oil and air for combustion. Read the chapter on Combustion in Boiler Furnaces, page 200.

Boiler Settings for Fuel Oil.—If good combustion is to be had at high rates of combustion—and boilers in nearly all plants are subjected to heavy overloads due to peaks or to emergencies—the setting must be high to insure sufficient furnace vclume for complete combustion. Where the products of combustion pass directly among the tubes, as in vertically baffled water-tube boilers, the setting should be such as to give at least 72 in. from the bottom front headers to the floor, measured vertically. For stationary water-tube boilers a furnace volume giving 80 cu. ft. per burner of 350 lb. of oil per hr. will produce good combustion at ratings well above 200 per cent. builder's rating.

Combustion or furnace volume is here meant as that space below, or below and in front of the boiler tubes (water-tube boilers), and below or in front of the shell of horizontal tubular boilers, also that space in back of the rear tube sheet. Space in and around

NUMBER OF HAMMEL BURNERS FOR DIFFERENT WIDTH B. & W. TYPE BOILERS

No. of tubes wide	Width of fire-box, in.	No. of burners	No. of ashpit doors	No. of air slots per burner
5	39	1	1	24
6	46	1	1	24
7	53	1	1	24
8	60	1	1	30
9	67	1	1	30
10	74	2	2	24
12	88	2	2	24
14	102	2	2	30
16	116	2	2	30
18	130	3	3	30
21	151	3	3	30
24	172	4	4	30
27	193	4	4	30

the heating surface is not here considered furnace volume, except in internally fired boilers.

A common practice now is to install 1 burner for each fire-door of a B. & W. type water-tube boiler.   The capacity of the burners for the boilers of various capacities are as follows:

The burner has a capacity up to 500 hp., and the size of the air slots depends upon the rated horsepower of the boiler; the capacity of the burner is intentionally governed by the amount of air supplied for combustion, *i.e.*, by the number and size of the air slots provided.   The burner or furnace usually employed is the back-shot.

In a properly designed furnace the grate bars are removed and a fire-brick floor with carefully planned air openings is laid on pieces of 2-in. pipe extending across the fire-box.   The air supply is admitted through these openings in the furnace floor so that it will come in close contact with the atomized oil and complete combustion will take place before the gases come in contact with the heating surface of the boiler.

Furnace Temperatures and Fire-brick.—Temperatures up to 3200 B.t.u. are found in boilers using fuel oil.   If the excess air is decreased too much these high temperatures will likely be produced.   There are refractory materials that will stand up under this temperature; but the ordinary fire-brick deteriorates rapidly if such high temperature is maintained constant over long periods, especially if the brick carries much of a load.   When this temperature is only periodic, as it usually is, the brick gives good service.

The best quality brick should be selected for oil-burning boilers. Glass is a good thing to throw into the furnace to glaze the bottom or furnace floor.   According to E. H. Peabody the Babcock & Wilcox Co. has good results with a wash for making joints in fire-brick, the wash being composed of 15 parts (by weight) of fire clay (ordinary), 5 parts carborundum sand, and 1 part silicate of soda.   Any brick or clay composed of diatomaceous earth makes excellent refractory material.   For oil-burning fur-

naces particularly the brick should have a low coefficient of expansion, neither should it shrink under the furnace temperature.

A 9 in. brick that will not expand more than $\frac{1}{8}$ in. and which will not melt or become plastic under the furnace temperature will serve well under severe conditions. Bricks that expand less than this are available on the market.

A good brick for fuel-oil furnaces has the following analysis: silica, 56.15 per cent.; alumina, 33.29; peroxide of iron, 0.59; lime, 0.17; magnesia, 0.121; water and inorganic matter. This brick is of New Jersey clay.

Where bolts, angle-iron, channel-iron or beams are used to support or hold fire-brick in the boiler furnace, extreme care must be exercised to provide adequate ventilation to cool them.

Heat Units Required by the Boiler.—The reader's conception of the requirements of an oil burner will be the better if he has a knowledge of the heat required by the boiler to enable it to develop rating, or more or less. For those who have not looked at the matter from this angle the following is given:

A boiler horsepower is 34.5 lb. of water evaporated into steam from and at 212 deg. F. This is equivalent to

$$970.4 \times 34.5 = 33{,}479 \; \textit{B.t.u. per hr.}$$

In other words 33,479 B.t.u. must be supplied per boiler horsepower-hour when the boiler efficiency is 100 per cent. Of course boilers do not operate with efficiencies of 100 per cent. The common efficiencies are from 40 and 55 per cent. for run-down or poorly operated plants to 70 to 80 per cent. for top-notch plants.

How much oil must be supplied per hour to get rated capacity from a 400-hp. boiler, oil 18,600 B.t.u. per lb., feedwater 212 deg. F. and boiler efficiency 78 per cent.?

The heat units required is

$$400 \; \textit{hp.} \times \frac{33{,}479}{0.78} = 17{,}168{,}800 \; \textit{B.t.u. per hr.}$$

Then the oil needed is

$$\frac{17{,}168{,}800}{18{,}600} = 923 \; \textit{lb. per hr.}$$

A 400-hp. Babcock & Wilcox boiler has three doors, therefore each burner must handle

$$\frac{923}{3} = 308 \; lb. \; per \; hr.$$

It is the author's opinion that a flat flame burner is superior to all others where the oil is atomized by steam or air, and on the whole the author prefers steam for atomizing, at least for stationary boilers.

Steam Required for Atomization.—The usual burner in first-class condition will require 2 per cent. of the steam generated by the boiler. Thus a 400-hp. boiler at rating will require for atomization

$$400 \times 34.5 \times 0.02 = 276 \; lb. \; per \; hr.$$

Care of the Burner.—The success and efficiency of oil-burning boilers depend largely upon the thorough atomization of the oil. With the chapter on combustion in mind the reader will clearly see why this is so. With the heavy oils some little sediment finds its way to the burner and, in passing through it wears the surface of the spreader so that in time there is poor atomization. The spreaders or tip pieces are of steel and are renewable, cost little and are always available. Needless to say that they should be renewed before too badly worn.

The reader should get the catalog of burner manufacturers for complete description of burners.

The author is impressed by a burner, Fig. 22, recently developed by Dr. W. N. Best of New York for using oil as an auxiliary fuel. It may be installed in the front or side wall of the furnace; the adjustable air opening insures excellent air control for all rates of combustion, and avoids leakage of air into the furnace at this point when the burner is not in use, as the opening may be entirely closed. It is made in capacities up to approximately 1000 lb. of oil per hr. maximum per burner.

Draft for Oil-burning Boilers.—Compared with coal-fired boilers oil-fired boilers are exceedingly sensitive to changes in draft.
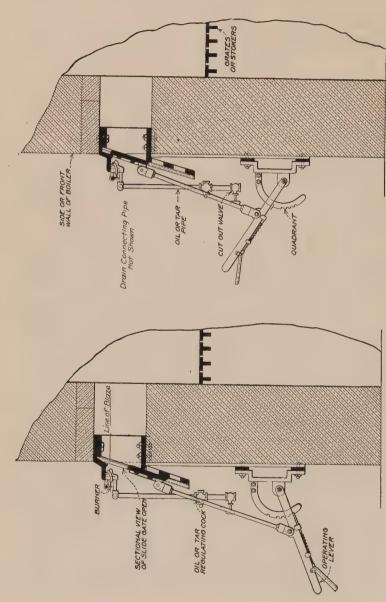
Fig. 22.—Burner for using oil as an auxiliary fuel; left, burner in operation; right, burner closed.

Best results are had with draft from 0.01 to 0.06 in., depending upon the capacity required of the boiler; this refers to draft measured in the furnace.

With oil the draft is not regulated the same as is done with coal.   With the former the ashpit doors are left open all the time, and the up-take damper regulates the volume of air admitted to the furnace.   To show the importance of close draft regulation the following figures from test by the Stone & Webster Construction Co. are given:

Oil temperature	Oil pressure	Atomizer pressure	Draft	CO_2
130	10	50	0.05	12
130	12	65	0.00	14

With oil particularly, a balanced-draft furnace is most desirable.

Air Required for Combustion.—The composition of the oil influences the air required; but ordinarily 200 cu. ft. at 60 deg. F. or 14 lb. per pound of oil is required for the very best operating conditions; 250 cu. ft. is more common.

Storage and Circulation of Oil.—The amount of oil to keep on hand at the plant depends, of course, upon the available supply and transportation conditions at and from the source of supply. If distant from the source provide for 2 to 3 weeks supply at the plant unless good reasons forbid.

For arrangement of storage tanks be governed by the city or insurance company requirements in your locality.

Proper preheating of the oil is too often neglected.   Every oil has characteristics that make some particular preheating temperature the best to use.   If the preheating temperature is too high, the oil will deposit carbon at the burner, seriously impairing the ability of the latter to function rightly by filling it with the carbon.   If too low, the oil will not vaporize well.

Carbon will be deposited usually if the temperature is more than 145 deg. F. at the burner.   A temperature of 80 or 90 deg. F. in the tanks gives good results.   The reason for heating the oil in the tanks is so it may be made liquid enough to be handled readily by the pumps; if too hot, it tends to gasify; if too cold, it

is too viscous to flow well.   Both of these give trouble in pumping.

The speed of the pumps should be regulated by a diaphragm valve connected to the main steam line.   This will increase or lessen the quantity of oil fed to the burners, as may be demanded.

The exhaust steam from the oil pump should be utilized to heat the oil before it reaches the burners.   Strainers in duplicate should be installed on the discharge side of each pump.   A circulating pipe system is essential, so that when starting the plant after it has been shut down and the oil allowed to become cold in the pipes, the burners can be bypassed and the oil circulated through the system and heated so that hot oil is supplied to the burners.   Provision should be made for removing any condensation from the steam lines leading to the burners, and these lines should be thoroughly insulated.

In plants that shut down on Saturday until Monday morning, it is necessary to install a small auxiliary boiler, which can be fired with wood or coal so that steam can be provided for atomizing and operating the pumps when the plant is to be started. These pumps are fitted with relief valves so that should the pressure generated on the oil exceed the usual 25–35 lb., the surplus oil is discharged back into the tank through the return circulation pipe from the burners.

In case the tank has not been placed below the burners, but has been placed in an approved concrete or brick inclosure and the top of the tank is higher than the pump, the feed pipe from tank to pump is required to enter the tank at the top, thence extending to the bottom, to avoid gravity feed from tank to pump.   Shutoff valves are installed on feed and circulating pipes as near the tank as possible.

Tanks, Vent Pipes and Indicators.—Tanks are usually of 500 gal. capacity up, 20,000 gal. being large for boiler plants.   They should be coated on the outside with tar for protection against rust.   Tanks in basements of buildings are located about 3 ft. below floor level with all oil-conveying pipes arranged to drain the oil into the tank.   The outlet end of the vent pipe (1 in.) should rise well above ground level, terminate in a goose-neck,

the open end of which should face down and be covered with a 40-to-the-inch screen to prevent flare back of flame in case of ignition at this place. Glass gage oil level indicators are not desirable; but if used provide well against breakage.

Use lead gaskets in the oil-carrying lines; rubber is not suitable. Make up the threaded pipe joints with glycerine and litharge. W. N. Best recommends a mixture of 8 lb. of sodium carbide with 1 bu. of sawdust as a floor covering where leaking oil pipes may create a fire hazard.

Relative Cost of Oil and Coal.—No hard and fast rule can be given. All costs up to the time the fuel is delivered to the boiler plus other expenses entailed, as ash handling, etc., should be considered.

The chart, Fig. 23, prepared by F. L. Walls of the Rhode Island State College and published in *Power*, Mar. 13, 1917, provides a ready means of determining the cost per gallon of oil which will make the cost the same as with coal at various prices per long ton.

Example.—Find the cost of oil in cents per gallon which will make the cost equal to that with coal at $5 per long ton; heating value of oil 18,200 B.t.u. per lb., that of coal 14,000 B.t.u. per lb.

Drop vertically from heating value 18,200 at top of the chart to the intersection with the horizontal from heating value 14,000 at the right. Follow oblique line from this intersection upward toward left-hand corner of chart until curve AB is reached. From here follow oblique line toward lower left-hand corner to intersection with vertical from price of coal at $5, at the bottom. From here pass horizontally to the left, intersecting the ordinate of oil prices at $0.0305 per gal.

The chart is constructed on the assumption that 36 per cent. more can be paid for B.t.u. from oil than from coal, in accordance with the results of the foregoing data. While this figure will be suitable under average conditions, in certain cases it may well happen that, owing to peculiarities of the plant or to unusual and predominating importance of some advantage such as cleanliness, nicety of control, etc., this figure should be modified. For exam-
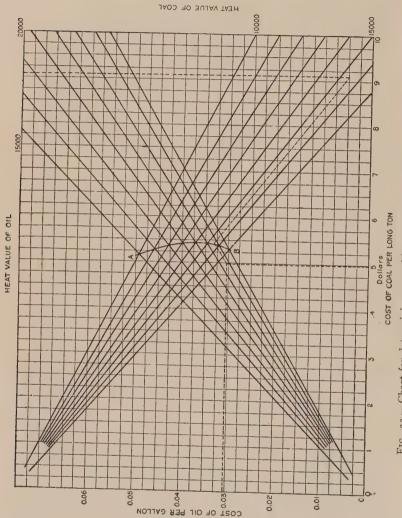
FIG. 23.—Chart for determining cost of burning fuel oil compared with coal.

ple, one operator finds that 50 per cent. more can be paid for oil than for coal. In this case the results from the chart should be multiplied by the ratio of the substituted percentage to 36. This would give as a result to the problem, $0.0305 \times \frac{50}{36} = 0.0424$.

The results of many tests under usual operating conditions have shown that on the average 84 B.t.u. from oil are equivalent to 100 B.t.u. from coal. With the same labor, boiler and other conditions, between 4 and 7 per cent. greater combined boiler efficiency may be expected with oil over coal. The labor required in the boiler room is of course greatly lessened, and ash removal and handling are totally eliminated.

As a rough figure applying to the average plant 30 per cent. more may be paid for oil delivered to the plant than for coal to produce a given boiler horsepower-hour output.

CO_2 with Fuel Oil.—All tables giving the CO_2 percentage, excess air, and preventable losses are, except for most general purposes, worthless unless they relate not only to a given class of fuel—solid, liquid or gaseous—but to particular fuels in each class. With fuel oil 13 to 15 per cent. represents the very best conditions of combustion in boiler furnaces.

Mixtures of Fuel Oil and Powdered Coal.—As this is written experiments are being conducted with a mixture of fuel oil and powdered coal, and the results even now are so successful that the fuel seems sure of success. Coal, 95 per cent. of which will pass through a screen of 200 mesh to the square inch, is mixed with fuel oil in the proportions of 64 per cent. oil (volume), 36 per cent. coal. Because of the greater density of the coal over oil the heating value per pound of the mixture is about the same as that of the straight coal. No special burner so far has been used, the Navy mechanical burner giving satisfactory service. Doubtless a steam atomized burner would be successful. The coal remains suspended in the oil for weeks without agitation. Widely applied, this fuel will do much to "stretch out" the diminishing fuel oil supply. It is less smoky than oil alone.

Table 12 will be found useful to the power-plant engineer.

TABLE 12.—COAL COST IN CENTS PER HORSEPOWER-HOUR AND KILOWATT-HOUR AT VARIOUS PRICES PER TON

Coal per kw.-hr., lb.	Coal per i. hp-hr., combined 90 %, efficiency lb.	Price of coal per ton of 2000 lb.									
		$1.50	$2.00	$2.50	$3.00	$3.50	$4.00	$4.50	$5.00	$5.50	$6.00
1.0	0.67	0.0750	0.1000	0.1250	0.1500	0.1750	0.2000	0.2250	0.2500	0.2750	0.3000
1.1	0.74	0.0825	0.1100	0.1375	0.1650	0.1925	0.2200	0.2475	0.2750	0.3025	0.3300
1.2	0.81	0.0900	0.1200	0.1500	0.1800	0.2100	0.2400	0.2700	0.3000	0.3300	0.3600
1.3	0.87	0.0975	0.1300	0.1625	0.1950	0.2275	0.2600	0.2925	0.3250	0.3575	0.3900
1.4	0.94	0.1050	0.1400	0.1750	0.2100	0.2450	0.2800	0.3150	0.3500	0.3850	0.4200
1.5	1.01	0.1125	0.1500	0.1875	0.2250	0.2625	0.3000	0.3375	0.3750	0.4125	0.4500
1.6	1.07	0.1200	0.1600	0.2000	0.2400	0.2800	0.3200	0.3600	0.4000	0.4400	0.4800
1.7	1.14	0.1275	0.1700	0.2125	0.2550	0.2975	0.3400	0.3825	0.4250	0.4675	0.5100
1.8	1.21	0.1350	0.1800	0.2250	0.2700	0.3150	0.3600	0.4050	0.4500	0.4950	0.5400
1.9	1.27	0.1425	0.1900	0.2375	0.2850	0.3325	0.3800	0.4275	0.4750	0.5225	0.5700
2.0	1.34	0.1500	0.2000	0.2500	0.3000	0.3500	0.4000	0.4500	0.5000	0.5500	0.6000
2.1	1.41	0.1575	0.2100	0.2625	0.3150	0.3675	0.4200	0.4725	0.5250	0.5775	0.6300
2.2	1.48	0.1650	0.2200	0.2750	0.3300	0.3850	0.4400	0.4950	0.5500	0.6050	0.6600
2.3	1.54	0.1725	0.2300	0.2875	0.3450	0.4025	0.4600	0.5175	0.5750	0.6325	0.6900
2.4	1.61	0.1800	0.2400	0.3000	0.3600	0.4200	0.4800	0.5400	0.6000	0.6600	0.7200
2.5	1.68	0.1875	0.2500	0.3125	0.3750	0.4375	0.5000	0.5625	0.6250	0.6875	0.7500
2.6	1.74	0.1950	0.2600	0.3250	0.3900	0.4550	0.5200	0.5850	0.6500	0.7150	0.7800
2.7	1.81	0.2025	0.2700	0.3375	0.4050	0.4725	0.5400	0.6075	0.6750	0.7425	0.8100
2.8	1.88	0.2100	0.2800	0.3500	0.4200	0.4900	0.5600	0.6300	0.7000	0.7700	0.8400
2.9	1.95	0.2175	0.2900	0.3625	0.4350	0.5075	0.5800	0.6525	0.7250	0.7975	0.8700
3.0	2.01	0.2250	0.3000	0.3750	0.4500	0.5250	0.6000	0.6750	0.7500	0.8250	0.9000
3.1	2.08	0.2325	0.3100	0.3875	0.4650	0.5425	0.6200	0.6975	0.7750	0.8525	0.9300
3.2	2.15	0.2400	0.3200	0.4000	0.4800	0.5600	0.6400	0.7200	0.8000	0.8800	0.9600
3.3	2.21	0.2475	0.3300	0.4125	0.4950	0.5775	0.6600	0.7425	0.8250	0.9075	0.9900
3.4	2.28	0.2550	0.3400	0.4250	0.5100	0.5950	0.6800	0.7650	0.8500	0.9350	1.0200
3.5	2.35	0.2625	0.3500	0.4375	0.5250	0.6125	0.7000	0.7875	0.8750	0.9625	1.0500
3.6	2.42	0.2700	0.3600	0.4500	0.5400	0.6300	0.7200	0.8100	0.9000	0.9900	1.0800
3.7	2.48	0.2775	0.3700	0.4625	0.5550	0.6475	0.7400	0.8325	0.9250	1.0175	1.1100
3.8	2.55	0.2850	0.3800	0.4750	0.5700	0.6650	0.7600	0.8550	0.9500	1.0450	1.1400
3.9	2.62	0.2925	0.3900	0.4875	0.5850	0.6825	0.7800	0.8775	0.9750	1.0725	1.1700
4.0	2.68	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000	1.0000	1.1000	1.2000
4.1	2.75	0.3075	0.4100	0.5125	0.6150	0.7175	0.8200	0.9225	1.0250	1.1275	1.2300
4.2	2.82	0.3150	0.4200	0.5250	0.6300	0.7350	0.8400	0.9450	1.0500	1.1550	1.2600
4.3	2.89	0.3225	0.4300	0.5375	0.6450	0.7525	0.8600	0.9675	1.0750	1.1825	1.2900
4.4	2.95	0.3300	0.4400	0.5500	0.6600	0.7700	0.8800	0.9900	1.1000	1.2100	1.3200
4.5	3.02	0.3375	0.4500	0.5625	0.6750	0.7875	0.9000	1.0125	1.1250	1.2375	1.3500
4.6	3.09	0.3450	0.4600	0.5750	0.6900	0.8050	0.9200	1.0350	1.1500	1.2650	1.3800
4.7	3.15	0.3525	0.4700	0.5875	0.7050	0.8225	0.9400	1.0575	1.1750	1.2925	1.4100
4.8	3.22	0.3600	0.4800	0.6000	0.7200	0.8400	0.9600	1.0800	1.2000	1.3200	1.4400
4.9	3.29	0.3675	0.4900	0.6125	0.7350	0.8575	0.9800	1.1025	1.2250	1.3475	1.4700
5.0	3.36	0.3750	0.5000	0.6250	0.7500	0.8750	1.0000	1.1250	1.2500	1.3750	1.5000

TABLE 12.—*Continued*

Coal per kw.-hr., lb.	Coal per i.hp.-hr., combined effi-ciency 90 %, lb.	Price of coal per ton of 2000 lb.								
		$6.50	$7.00	$7.50	$8.00	$8.50	$9.00	$9.50	$10.00	$10.50
1.0	0.67	0.3250	0.3500	0.3750	0.4000	0.4250	0.4500	0.4750	0.5000	0.5250
1.1	0.74	0.3575	0.3850	0.4125	0.4400	0.4675	0.4950	0.5225	0.5500	0.5775
1.2	0.81	0.3900	0.4200	0.4500	0.4800	0.5100	0.5400	0.5700	0.6000	0.6300
1.3	0.87	0.4225	0.4550	0.4875	0.5200	0.5525	0.5850	0.6175	0.6500	0.6825
1.4	0.94	0.4550	0.4900	0.5250	0.5600	0.5950	0.6300	0.6650	0.7000	0.7350
1.5	1.01	0.4875	0.5250	0.5625	0.6000	0.6375	0.6750	0.7125	0.7500	0.7875
1.6	1.07	0.5200	0.5600	0.6000	0.6400	0.6800	0.7200	0.7600	0.8000	0.8400
1.7	1.14	0.5525	0.5950	0.6375	0.6800	0.7225	0.7650	0.8075	0.8500	0.8925
1.8	1.21	0.5850	0.6300	0.6750	0.7200	0.7650	0.8100	0.8550	0.9000	0.9450
1.9	1.27	0.6175	0.6650	0.7125	0.7600	0.8075	0.8550	0.9025	0.9500	0.9975
2.0	1.34	0.6500	0.7000	0.7500	0.8000	0.8500	0.9000	0.9500	1.0000	1.0500
2.1	1.41	0.6825	0.7350	0.7875	0.8400	0.8925	0.9450	0.9975	1.0500	1.1025
2.2	1.48	0.7150	0.7700	0.8250	0.8800	0.9350	0.9900	1.0450	1.1000	1.1550
2.3	1.54	0.7475	0.8050	0.8625	0.9200	0.9775	1.0350	1.0925	1.1500	1.2075
2.4	1.61	0.7800	0.8400	0.9000	0.9600	1.0200	1.0800	1.1400	1.2000	1.2600
2.5	1.68	0.8125	0.8750	0.9375	1.0000	1.0625	1.1250	1.1875	1.2500	1.3125
2.6	1.74	0.8450	0.9100	0.9750	1.0400	1.1050	1.1700	1.2350	1.3000	1.3650
2.7	1.81	0.8775	0.9450	1.0125	1.0800	1.1475	1.2150	1.2825	1.3500	1.4175
2.8	1.88	0.9100	0.9800	1.0500	1.1200	1.1900	1.2600	1.3300	1.4000	1.4700
2.9	1.95	0.9425	0.0150	1.0875	1.1600	1.2325	1.3050	1.3775	1.4500	1.5225
3.0	2.01	0.9750	1.0500	1.1250	1.2000	1.2750	1.3500	1.4250	1.5000	1.5750
3.1	2.08	1.0075	1.0850	1.1625	1.2400	1.3175	1.3950	1.4725	1.5500	1.6275
3.2	2.15	1.0400	1.1200	1.2000	1.2800	1.3600	1.4400	1.5200	1.6000	1.6800
3.3	2.21	1.0725	1.1550	1.2375	1.3200	1.4025	1.4850	1.5675	1.6500	1.7325
3.4	2.28	1.1050	1.1900	1.2750	1.3600	1.4450	1.5300	1.6150	1.7000	1.7850
3.5	2.35	1.1375	1.2250	1.3125	1.4000	1.4875	1.5750	1.6625	1.7500	1.8375
3.6	2.42	1.1700	1.2600	1.3500	1.4400	1.5300	1.6200	1.7100	1.8000	1.8900
3.7	2.48	1.2025	1.2950	1.3875	1.4800	1.5725	1.6650	1.7575	1.8500	1.9425
3.8	2.55	1.2350	1.3300	1.4250	1.5200	1.6150	1.7100	1.8050	1.9000	1.9950
3.9	2.62	1.2675	1.3650	1.4625	1.5600	1.6575	1.7550	1.8525	1.9500	2.0475
4.0	2.68	1.3000	1.4000	1.5000	1.6000	1.7000	1.8000	1.9000	2.0000	2.1000
4.1	2.75	1.3325	1.4350	1.5375	1.6400	1.7425	1.8450	1.9475	2.0500	2.1525
4.2	2.82	1.3650	1.4700	1.5750	1.6800	1.7850	1.8900	1.9950	2.1000	2.2050
4.3	2.89	1.3975	1.5050	1.6125	1.7200	1.8275	1.9350	2.0425	2.1500	2.2575
4.4	2.95	1.4300	1.5400	1.6500	1.7600	1.8700	1.9800	2.0900	2.2000	2.3100
4.5	3.02	1.4625	1.5750	1.6875	1.8000	1.9125	2.0250	2.1375	2.2500	2.3625
4.6	3.09	1.4950	1.6100	1.7250	1.8400	1.9550	2.0700	2.1850	2.3000	2.4150
4.7	3.15	1.5275	1.6450	1.7625	1.8800	1.9975	2.1150	2.2325	2.3500	2.4675
4.8	3.22	1.5600	1.6800	1.8000	1.9200	2.0400	2.1600	2.2800	2.4000	2.5200
4.9	3.29	1.5925	1.7150	1.8375	1.9600	2.0825	2.2050	2.3275	2.4500	2.5725
5.0	3.36	1.6250	1.7500	1.8750	2.0000	2.1250	2.2500	2.3750	2.5000	2.6250

TABLE 12.—*Continued*

Coal per kw.-hr., lb.	Coal per i.hp.-hr., combined 90% efficiency lb.	Price of coal per ton of 2000 lb.								
		$11.00	$11.50	$12.00	$12.50	$13.00	$13.50	$14.00	$14.50	$15.00
1.0	0.67	0.5500	0.5750	0.6000	0.6250	0.6500	0.6750	0.7000	0.7250	0.7500
1.1	0.74	0.6050	0.6325	0.6600	0.6875	0.7150	0.7425	0.7700	0.7975	0.8250
1.2	0.81	0.6600	0.6900	0.7200	0.7500	0.7800	0.8100	0.8400	0.8700	0.9000
1.3	0.87	0.7150	0.7475	0.7800	0.8125	0.8450	0.8775	0.9100	0.9425	0.9750
1.4	0.94	0.7700	0.8050	0.8400	0.8750	0.9100	0.9450	0.9800	1.0150	1.0500
1.5	1.01	0.8250	0.8625	0.9000	0.9375	0.9750	1.0125	1.0500	1.0875	1.1250
1.6	1.07	0.8800	0.9200	0.9600	1.0000	1.0400	1.0800	1.1200	1.1600	1.2000
1.7	1.14	0.9350	0.9775	1.0200	1.0625	1.1050	1.1475	1.1900	1.2325	1.2750
1.8	1.21	0.9900	1.0350	1.0800	1.1250	1.1700	1.2150	1.2600	1.3050	1.3500
1.9	1.27	1.0450	1.0925	1.1400	1.1875	1.2350	1.2825	1.3300	1.3775	1.4250
2.0	1.34	1.1000	1.1500	1.2000	1.2500	1.3000	1.3500	1.4000	1.4500	1.5000
2.1	1.41	1.1550	1.2075	1.2600	1.3125	1.3650	1.4175	1.4700	1.5225	1.5750
2.2	1.48	1.2100	1.2650	1.3200	1.3750	1.4300	1.4850	1.5400	1.5950	1.6500
2.3	1.54	1.2650	1.3225	1.3800	1.4375	1.4950	1.5525	1.6100	1.6675	1.7250
2.4	1.61	1.3200	1.3800	1.4400	1.5000	1.5600	1.6200	1.6800	1.7400	1.8000
2.5	1.68	1.3750	1.4375	1.5000	1.5625	1.6250	1.6875	1.7500	1.8125	1.8750
2.6	1.74	1.4300	1.4950	1.5600	1.6250	1.6900	1.7550	1.8200	1.8850	1.9500
2.7	1.81	1.4850	1.5525	1.6200	1.6875	1.7550	1.8225	1.8900	1.9575	2.0250
2.8	1.88	1.5400	1.6100	1.6800	1.7500	1.8200	1.8900	1.9600	2.0300	2.1000
2.9	1.95	1.5950	1.6675	1.7400	1.8125	1.8850	1.9575	2.0300	2.1025	2.1750
3.0	2.01	1.6500	1.7250	1.8000	1.8750	1.9500	2.0250	2.1000	2.1750	2.2500
3.1	2.08	1.7050	1.7825	1.8600	1.9375	2.0150	2.0925	2.1700	2.2475	2.3250
3.2	2.15	1.7600	1.8400	1.9200	2.0000	2.0800	2.1600	2.2400	2.3200	2.4000
3.3	2.21	1.8150	1.8975	1.9800	2.0625	2.1450	2.2275	2.3100	2.3925	2.4750
3.4	2.28	1.8700	1.9550	2.0400	2.1250	2.2100	2.2950	2.3800	2.4650	2.5500
3.5	2.35	1.9250	2.0125	2.1000	2.1875	2.2750	2.3625	2.4500	2.5375	2.6250
3.6	2.42	1.9800	2.0700	2.1600	2.2500	2.3400	2.4300	2.5200	2.6100	2.7000
3.7	2.48	2.0350	2.1275	2.2200	2.3125	2.4050	2.4975	2.5900	2.6825	2.7750
3.8	2.55	2.0900	2.1850	2.2800	2.3750	2.4700	2.5650	2.6600	2.7550	2.8500
3.9	2.62	2.1450	2.2425	2.3400	2.4375	2.5350	2.6325	2.7300	2.8275	2.9250
4.0	2.68	2.2000	2.3000	2.4000	2.5000	2.6000	2.7000	2.8000	2.9000	3.0000
4.1	2.75	2.2550	2.3575	2.4600	2.5625	2.6650	2.7675	2.8700	2.9725	3.0750
4.2	2.82	2.3100	2.4150	2.5200	2.6250	2.7300	2.8350	2.9400	3.0450	3.1500
4.3	2.89	2.3650	2.4725	2.5800	2.6875	2.7950	2.9025	3.0100	3.1175	3.2250
4.4	2.95	2.4200	2.5300	2.6400	2.7500	2.8600	2.9700	3.0800	3.1900	3.3000
4.5	3.02	2.4750	2.5875	2.7000	2.8125	2.9250	3.0375	3.1500	3.2625	3.3750
4.6	3.09	2.5300	2.6450	2.7600	2.8750	2.9900	3.1050	3.2200	3.3350	3.4500
4.7	3.15	2.5850	2.7025	2.8200	2.9375	3.0550	3.1725	3.2900	3.4075	3.5250
4.8	3.22	2.6400	2.7600	2.8800	3.0000	3.1200	3.2400	3.3600	3.4800	3.6000
4.9	3.29	2.6950	2.8175	2.9400	3.0625	3.1850	3.3075	3.4300	3.5525	3.6750
5.0	3.36	2.7500	2.8750	3.0000	3.1250	3.2500	3.3750	3.5000	3.6250	3.7500

CHAPTER VI

COMBUSTION LOSSES IN BOILER OPERATION

The losses in boiler operation are so great and occur without noise or other obvious signs, except to the highly trained, and the standard method of testing boilers is so tedious that it is now the practice in well-conducted plants to frequently check up the efficiency, using the CO_2 content of the flue gases and the temperature of the outlet gases as a guide. The best description of this method that the writer has seen was given in *Power* by Haylett O'Neill; it follows:

The object is to point out the significance of a simple and cheap method for determining evaporative boiler efficiency. This method is to measure the average temperature of the flue gas where the gas leaves the boiler-heating surface, to analyze for CO_2 content an average sample of flue gas from the same source, and to apply these two determinations to the efficiency chart, Fig. 24. Thus, flue-gas
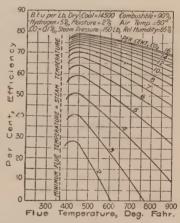
FIG. 24.—Boiler efficiency determined on flue gas temperature and CO_2.

temperature and CO_2 percentage are assumed to be the only variable factors of boiler efficiency. This is computed by dividing the difference between the heating value of the coal and the calculated losses by the heating value of the coal.

In calculating the total losses, certain operating conditions and accompanying losses actually variable, are assumed constant

and there is necessarily an error in the computed efficiency. However, where Eastern coals are burned, such error is usually less than 2.5 per cent., sufficiently precise for comparative results. It is well to note conditions under which such assumed losses may vary. For example, the refuse loss here is assumed constant, while it actually varies according to the coal and the design and the operation of the grates. The radiation loss is assumed equal to 4 per cent. of the boiler output at builder's rating. In very large units, the loss is probably nearer 2 per cent. A boiler in
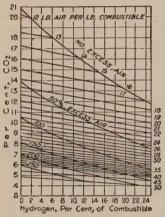
FIG. 25.—Possible CO_2 with various percentages of hydrogen in coal.

a cold climate, other things being equal, cannot be so commercially efficient as one surrounded by air averaging 90 deg. But the error from the foregoing assumption will, upon close analyses of the charts, be negligible compared with the losses accurately measured by the flue-gas temperature and the percentage of CO_2.

Heat losses may be divided into two classes: Those measured by CO_2 and flue temperature, and those measured by flue temperature only.

Loss in Dry Flue Gas.—By itself, the percentage of CO_2 does not even measure boiler efficiency. The greater the percentage of hydrogen the less will be the possible CO_2 percentage. Fig. 25 indicates a possibility of 20.9 per cent. CO_2 from the burning of pure carbon and an impossibility of greater than 18.5 to 19 per cent. CO_2 for soft coal containing 4 or 5 per cent. hydrogen.

A plain Orsat CO_2 analysis of an average tank sample of gas collected over a given period shows all the flue-gas analytical data of interest.

The heat loss in dry gas at flue temperature is calculated as follows:

Heat Loss (*B.t.u. per lb. of dry coal*) $= WS(Tf - Ta)$

where

$W =$ Pounds of flue gas per pound of coal determined from proximate analysis of coal and Fig. 24;

$S =$ Specific heat of flue gas, assumed constant for all temperatures;

$Ta =$ Temperature of the air assumed at 80 deg. F.;

$Tf =$ Temperature of flue gas.

Loss Indicated by Presence of CO in Flue Gas.—Carbon monoxide (CO) is a result of the incomplete combustion of carbon
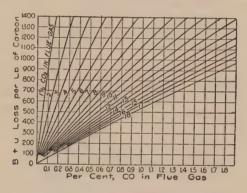
FIG. 26.—Loss on account of incomplete combustion of carbon.

and oxygen, and while the loss from it is not strictly measured by the percentage of CO_2, it is affected thereby. For example, from Fig. 26, 0.1 per cent. CO shows a loss of 320 heat units per pound of carbon when the flue gas is 3 per cent. CO_2, but a loss of only 70 units when the CO_2 is 14 per cent.; that is, the less the excess air the less the proportionate loss from incomplete combustion of coal. CO indicates a shortage of air required for complete combustion either locally or generally, and usually results from too heavy a fire for a given draft, stratification of gas on account of an uneven fire, or from the passage of hot CO_2 over soot-laden tubes where it combines with enough carbon to form CO. Thus, CO_2 plus $CO = 2CO$. Most furnaces get

too much air rather than too little, and generally CO. is absent In the calculated efficiency chart, CO is assumed at 0.1 per cent.

Loss on Account of Moisture in the Air Supplied for Combustion.—All air contains moisture indicated in definite porportions by the wet- and dry-bulb temperatures as illustrated in Fig. 27, These temperatures, together with the percentage of CO_2. measure the ratio of moisture in air per pound of fuel. The loss from superheating this moisture to flue temperature is usually inconsiderable. In the efficiency chart it is calculated at about 12 B.t.u. per pound of coal burned.
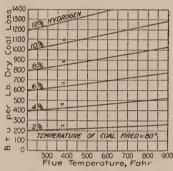
FIG. 27.—Loss on account of hydrogen in air for combustion.

Loss on Account of Refuse.—Soft-coal refuse usually contains both volatile and fixed carbon; but generally the volatile is negligible. Fig. 28 shows the loss from unburned combustible calculated on the fixed-carbon basis. This loss depends not only upon the percentage of combustible in the refuse, but also upon the percentage of ash in the coal. The poorer the coal with respect to ash the higher will be the refuse loss. The quality of the coal and the design and operation of the furnace are factors in boiler efficiency. The loss due to sensible heat of the refuse shown in Fig. 29 is small.

Loss on Account of Moisture in the Fuel.—Moisture fed to the furnace with the coal, evaporated and superheated to the flue temperature, carries heat up the chimney. Ordinarily, as shown in Fig. 30, this is a minute loss.

Loss on Account of Hydrogen in the Fuel.—When 1 lb. of hydrogen is burned, 9 lb. of water vapor is formed. Consequently, when a pound of coal containing 5 per cent. hydrogen is burned, 0.45 lb. water vapor is formed and this as superheated steam carries about 550 heat units to the chimney. It will appear from

Fig. 30 that this loss, in the case of fuel oils and natural gas high in hydrogen, may be very high.

Since the bomb calorimeter, measuring the heat value of coal, is jacketed by cold water, to absorb the latent heat in the water
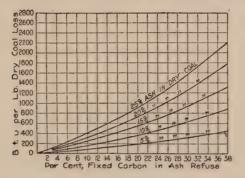
FIG. 28.—Heat loss to ashpit from unburned carbon.

vapor burned hydrogen, the coal is credited with the 550 heat units which must be lost in the flue. That is, water vapor under atmospheric pressure will not condense at temperatures above
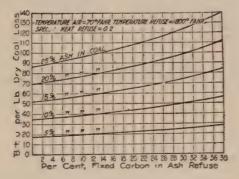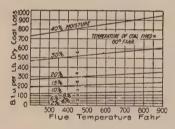
FIG. 29.—Sensible heat loss to the ashpit.

212 deg. F.; and since the flue temperature is always higher than this, the latent heat in the flue-gas vapor cannot be reclaimed to produce steam.

TABLE 13.—TEST ON SPECIAL 2365-HP. STIRLING BOILER AT DELRAY STATION, DETROIT, MICH., BY D. S. JACOBS, 1910, JOURNAL A.S.M.E.

Flue temperature, deg. F. observed	CO_2, per cent. observed	Efficiency by regular method	Efficiency by chart	Efficiency, per cent. error of chart
480	14.33	79.88	79.0	—0.88
483	14.40	81.15	79.0	—2.15
576	11.95	77.84	74.0	—3.84
670	14.74	75.78	75.0	—0.78
636	14.69	76.73	75.5	—1.23
487	11.86	77.90	75.5	—2.45
493	13.69	80.29	77.5	—2.78
575	14.00	77.07	76.0	—1.07
647	14.20	76.42	75.0	—1.42
651	15.45	75.84	75.5	—0.34

Loss on Account of Boiler Radiation.—Depending upon the design of the setting, the radiation loss is about 4 per cent. of the

FIG. 30.—Heat loss due to moisture in coal.

FIG. 31.—Heat loss on account of radiation.

rated boiler output. That is, from a 500-hp. boiler, the radiation loss is about $0.04 \times 500 \times 33,479 = 669,580$ B.t.u. per hour. The factor 33,479 is the B.t.u. equivalent of a boiler horsepower or $970.4 \times 34.5 = 33,479$. The loss per unit of output will vary inversely as the output; that is, it may be infinity at zero output, and it approaches zero as the output indefinitely increases. The maximum flue-gas temperature at zero is that of boiler water. Its

rise above boiler-water temperature varies almost directly with the load.   Consequently, the radiation loss per unit of output and per pound of coal fired varies inversely as the rise in flue temperature above the steam temperature.   This is illustrated by the hyperbolic curve of radiation loss per pound of fuel in Fig. 31.

Total Heat Losses.—The general conditions assumed constant to calculate the efficiency and heat-loss curves are as follows: Combustible in coal, 90 per cent.; hydrogen in coal, 5 per cent.;

Fig. 32.

Fig. 33.

Fig. 34.
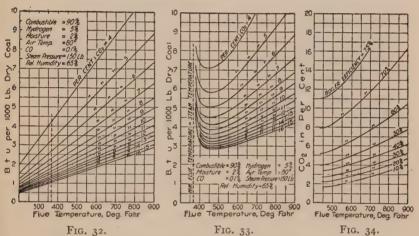
Fig. 32.—Furnace losses measured by CO_2 and flue temperature.

Fig. 33.—Furnace losses measured by furnace temperature with and independent of CO_2.

Fig. 34.—Relation between CO_2 and flue temperatures for constant boiler efficiency.

moisture in coal, 2 per cent.; air temperature, 80 deg. F.; CO, 0.1 per cent.; steam pressure, 150 lb. gage; relative humidity, 65 per cent.; combustible in refuse, 20 per cent.   With these assumptions Figs. 31 and 32 respectively show heat losses measured by CO_2 percentage and flue-gas temperature and those measured only by flue-gas temperature.   The combined losses are shown in Fig. 33.

Except for the radiation losses, the total heat losses are accurately determined and the error in radiation loss is practically

negligible at flue temperatures above 475 deg. F. Little interest is attached to points of lower temperatures.

It appears that for any percentage of CO_2 there is a certain flue temperature at which the total heat losses per pound of fuel is a minimum, and this is the point of maximum efficiency.

To compute the efficiencies in Fig. 34, 200 B.t.u. were added to the losses to account for undetermined losses. Tables 13 and 14 illustrate the close practical accuracy of the curves.

More clearly in Fig. 34 are shown the relative values of CO_2 percentage and flue temperatures in the determination of boiler efficiency. Suppose a boiler at 70 per cent. efficiency shows 10

TABLE 14.—TEST ON 650-HP. BABCOCK & WILCOX BOILER AT WATERSIDE STATION, NEW YORK CITY, BY THE NEW YORK EDISON CO., 1911

Flue temperature, deg. F. observed	CO_2, per cent. observed	Efficiency by regular method	Efficiency by chart	Efficiency, per cent. error of chart
523	12.4	74.3	75.4	+1.1
533	11.7	75.9	74.7	−1.2
541	11.4	75.2	74.1	−1.1
497	13.7	75.5	77.2	+1.7
505	11.8	77.0	75.4	−1.6
509	11.1	76.5	74.6	−1.9
491	11.2	75.1	74.8	−0.3
512	12.2	76.9	75.5	−1.4
574	11.2	73.9	72.8	−1.1
571	16.5	73.2	77.5	+4.3
665				
695				
505	10.5	75.1	73.8	−1.3
595	14.3	73.4	76.0	+2.6
555	13.0	76.8	75.4	−1.4
571	11.9	74.5	73.8	−0.7
507	13.4	80.1	76.8	−3.3

per cent. CO_2 and 610 deg. F. flue temperature. Let the air leakage of the boiler setting be eliminated and the firing be improved so that the CO_2 is raised to 12 per cent., but at the same

time let the baffles deteriorate and allow the soot to build on the tubes until the flue temperature rises to 710 deg. F.   Then the efficiency will still be about 70 per cent., and all the good operating work will be nullified by the slovenly maintenance.

A draft gage used in connection with Figs. 35 and 36 shows data necessary to determine approximately the rate of combustion, and from this and the efficiency determination the boiler output may be closely estimated.
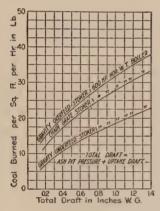
FIG. 35.—Eastern soft coal combustion rate on different stokers.
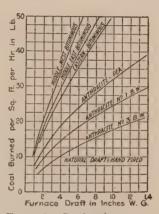
FIG. 36.—Combustion rates with hand-firing, natural draft.

Thus, valuable boiler-operating data can be obtained for practical use, through simple and cheap instruments.

Unpreventable Combustion Losses.—The following from an article in *Power* by Haylett O'Neill will assist the engineer in calculating combustion losses.

It never is possible in the ordinary boiler furnace to transform the total heat units in the coal, as determined by the calorimeter, into equivalent heat of the steam.   It is the purpose of the following to show the effect of these losses on the ultimate value of coal for steaming purposes.   The necessary losses are due to the following causes:

1. To heating the theoretical quantity of air required for com-

bustion from the outside-air temperature to the up-take-gas temperature.

2. To heating the combustible from the outside-air temperature to the temperature of the exit gases.

3. To evaporating and superheating the moisture in the coal from the outside-air temperature to the boiler temperature.

4. To evaporating and superheating the moisture formed by burning hydrogen at outside temperature to the temperature of the exit gases.

5. To heating the moisture in the theoretical amount of air required for combustion, from the outside temperature to the temperature of the exit gases.

In addition there are other losses practically necessary and due to the following causes:

6. To sensible heat in the refuse to the ashpit with a practical minimum percentage of combustible.

7. To unconsumed combustible in the ash with a practical minimum percentage of combustible.

The effect of climate is obvious, and there will be greater necessary losses in winter than in summer.   For example, assume:

1. Boiler pressure, lb. abs., 165.

2. Boiler-water temperature, deg. F., 366.

3. Outside-air temperature, deg. F., 70.

4. Relative humidity, per cent., 70.

5. Moisture in coal, per cent., 2.

6. Hydrogen in coal, per cent., 5.

7. Practical minimum combustible in ash, per cent., 25.

8. Temperature of ash, deg. F., 1800.

9. Ash in coal, per cent., 6.

10. B.t.u. (dry), per lb., 14,500.

11. Specific heat of refuse and coal, B.t.u., 0.2.

12. Mean specific heat of vapor in atmosphere, B.t.u., 0.46.

13. Dry coal = ash + hydrogen + carbon.   This is approximately correct for high-grade Eastern coals—that is, neglecting the effect of sulphur, nitrogen and oxygen.

14. Specific heat of air, B.t.u., 0.2375.

Fig. 37 shows the relationship between percentage of CO_2, excess air, and hydrogen contained in the fuel, and the pounds of air per pound of combustible. For average good-grade coal the percentage of hydrogen is about 5. Referring to Fig. 37, with no excess air and 5 per cent. hydrogen, the pounds of air per pound of combustible equal 12.7.
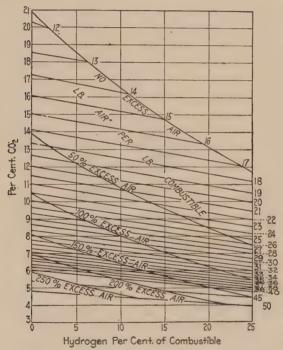
FIG. 37.—Relation between hydrogen, excess air and CO_2.

The losses then are as follows:

1. Due to heating theoretical air required:

Air required per pound of coal $(1 - 0.06)\ 12.7 = 11.92$ lb.

Heat loss per pound of coal, $0.2375 \times 11.92 \times (366 - 70) = 839$ B.t.u.

2. Due to evaporating and superheating moisture in coal (Values from Marks and Davis' Steam Tables):

H at 14.7 lb. abs. and 366 deg. F. = 1223 B.t.u.

h at 70 deg. F. = 38 B.t.u.

Heat loss, 0.02 × (1223 − 38) = 24 B.t.u.
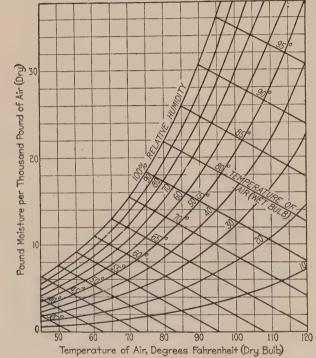
FIG. 38.—Ratio of moisture to dry air for various humidities.

3. Due to heating combustible:

Heat loss (1 − 0.06) × 0.2 × (366 − 70) = 56 B.t.u.

4. Due to evaporating and superheating moisture formed by burning hydrogen:

Atomic weight of H = 1, atomic weight of O = 16.

Pounds of vapor per pound of hydrogen, $\dfrac{2 + 16}{2} = 9.$

Heat loss, $9 \times 0.05 \times (1223 - 38) = 533$ B.t.u.

Fig. 38 shows the ratio of moisture to dry air for various relative humidities at different air temperatures, as determined by the ordinary dry-bulb thermometer. With 70 deg. F. air temperature and 70 per cent. relative humidity, the moisture per pound of dry air equals 0.0108 pound.

5. Due to heating moisture in air:

Heat loss $= 0.0108 \times 11.92 \times 0.46 \times (366 - 70) = 17$ B.t.u.

Total heat loss $= 839 + 24 + 56 + 533 + 17 = 1469$ B.t.u.

From this should be deducted loss due to heating the oxygen required for the combustion of the hydrogen that has been duplicated.

Pounds oxygen per pound of hydrogen, 8.

Heat loss, $0.05 \times 8 \times 0.2375 \times (366 - 70) = 29$ B.t.u.

Heat loss, net total, $1469 - 29 = 1440$ B.t.u.

Maximum possible efficiency $= \dfrac{14,500 - 1440}{14,500} = 90$ per cent.

6. Loss due to sensible heat in refuse:

$$\frac{0.06}{1 - 25} \times 0.2 \times (1800 - 70) = 28 \; B.t.u.$$

7. Loss due to unconsumed combustible in refuse:

$$\frac{0.25(0.06)}{1 - 25} \times 14,610 = 292 \; B.t.u.$$

Total refuse losses $= 320$ B.t.u.

Total, all losses $= 1763$ B.t.u.

Practical ideal efficiency $= \dfrac{14,500 - 1763}{14,500} = 88$ per cent.

1. Heat loss on account of warming air:

$$\frac{12.7 \times 296 \times 0.2375 \; (100 \; per \; cent. \; ash)}{100}$$

$$= 8.94 \; B.t.u. \; (100 \; per \; cent. \; ash)$$

Heat loss on account of heating combustible:

$$\frac{0.2 \times 296 \times (100 \; per \; cent. \; ash)}{100}$$

$$= 0.5920 \; B.t.u. \; (100 \; per \; cent. \; ash)$$

3. Heat loss on account of moisture in coal:

$$\frac{Per\ cent.\ moisture}{100} \times 1185 = 11.85 \times per\ cent.\ moisture;$$

assume this to be 1 per cent., or 12 B.t.u. constant.

4. Heat loss on account of hydrogen = 533 B.t.u.; assume 5 per cent. H.
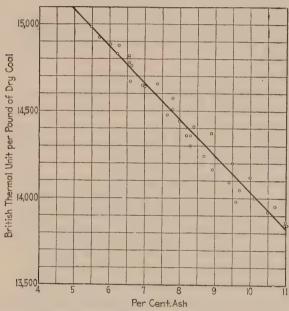
FIG. 39.—Relation between ash and heat value.

5. Heat loss on account of moisture in air = 17 B.t.u.; assume this to be constant.

6. Heat loss on account of sensible heat refuse:

$$\frac{Per\ cent.\ ash}{0.75} \times 0.2 \times 1730 = 4.62 \times per\ cent.\ ash;$$

assuming 25 per cent. combustible in refuse.

7. Heat loss on account of unconsumed combustible in refuse:

$$\frac{25}{75} \times \frac{per\ cent.\ ash}{100} \times 14,610 = 48.7 \times per\ cent.\ ash;$$

assuming 25 per cent. combustible refuse.
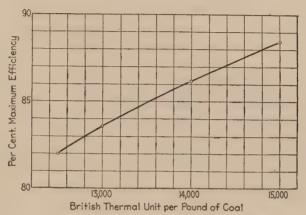
FIG. 40.—Theoretical thermal efficiency with West Virginia coal.
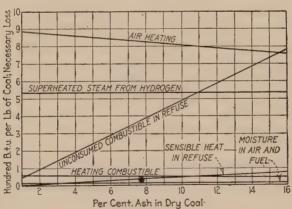
FIG. 41.—Separate and total necessary losses.

Summing up all losses, we have:

Necessary losses in B.t.u. = 1486 + 43.8 × per cent. ash.

For good West Virginia coal, analyses taken from a bulletin of the United States Geological Survey show the following relationship between percentage of ash and heat content.

B.t.u. per pound dry is $16,130 - 210 \times$ per cent. ash.   This is shown graphically in Fig. 39.

$$Maximum\ efficiency = \frac{B.t.u. - (1486 + 43.8\ per\ cent.\ ash)}{B.t.u.}$$

Substituting ash in terms of B.t.u.,

$$Maximum\ efficiency = \frac{1.208\ B.t.u. - 4832}{B.t.u.}$$

This relationship is shown in Fig. 40.

Fig. 41 shows the separate and total necessary losses as calculated.

See Chapter VIII for the influence of combustion rates on boiler capacity and combined boiler and furnace efficiency.

CHAPTER VII

OPERATING MECHANICAL STOKERS

The chapter on Boiler Settings, page 210, should be frequently referred to in connection with this chapter.

Knowledge of Combustion Necessary.— No person can successfully operate stokers or successfully supervise their operation unless he has a working knowledge of the factors which influence combustion in the boiler furnace. These are set forth in Chapter II, and the reader not well versed in practical combustion is asked to study Chapter II before taking up the operation of stokers.

Types of Stokers.—There are five types of stokers, namely, "hand" (Huber type), chain-grate, over-feed, side-feed and underfeed. The latter may be divided into two classes, single-retort and multiple-retort.

Some Representative Stokers

Hand.—Huber, Stevens and Files.

Chain-grate.—Laclede-Christy, Babcock & Wilcox, Illinois, Coxe (anthracite), Playford, Green, and McKensie.

Over-feed (Step Grates).—Westinghouse-Roney, Wetzel, Wilkinson and Acme.

Side-feed (Over-feed, Step Grates).—Murphy, Detroit and Model.

Multiple-retort Underfeed.—Westinghouse, Taylor, Riley.

Single-retort Underfeed.—Jones, Type E, American, Moloch.

Sprinkler.—Swift and Vulcan.

Fuels for Different Stokers.—Chain-grate—high volatile (28 to 49 per cent.), high ash (10 to 20 per cent.) coals, also natural

lignites and slack, each high in moisture—15 to 30 per cent. These stokers under horizontally baffled boilers or in a furnace with a long coking arch and large volume are admirably suited to the Middle Western coals. For high moisture coals and natural lignites (uncarbonized) a long reflecting arch extending from the bridge-wall forward sufficiently to sweep the flame over or near the incoming green fuel and to radiate heat to it to drive off the moisture is essential to successful operation. The author prefers to restrict the gas opening between coking arch and reflecting arch to an area just adequate to avoid excess draft losses at the highest combustion rate desired. The maximum rating is about 200 to 250 per normal rating of the boiler—say 48 lb. coal per sq. ft. of grate per hr.

Over-feed and Side-feed.—These stokers when provided with long combustion arches successfully burn nearly all kinds of coal. Look out for avalanching with some coals. Maximum capacity is seldom above 200 per cent. normal boiler rating.

Underfeed.—These stokers successfully burn nearly all kinds of bituminous coals and mixtures of bituminous and fine anthracite—provided the furnace is suitable. The multiple retort underfeed stokers are particularly suited to boilers intended to operate at ratings reaching 500 per cent. builder's rating. They burn lignites quite well when the moisture has been dried out down to say, 15 per cent.

As yet no marked success has been made in burning mixtures of bituminous and anthracite coals on these stokers. They can be burned; but the persistent tendency of the fine anthracite to segregate gives serious trouble, even when there is no more than 10 per cent. culm or silt in the mixture. Trouble from segregation increases with the number of times the coal is handled or gravitated before it reaches the stoker hopper. Experiments made during the severe fuel shortage in 1918 showed that the multiple retort underfeed stoker can be made to burn fine anthracite unmixed, and coke breeze unmixed. One, and possibly all builders of these stokers, will guarantee 72 per cent. at builder's boiler

rating with coke breeze. The Coxe stoker is by far most suitable for any of the fine grades of anthracite.

Prime Advantage of the Stoker.—The prime advantage of the stoker lies in its ability to slowly distill the volatile matter from the coal. Many of its other advantages are due to this one. See the chapter on Combustion of Coal in Boiler Furnaces, page 200.

Other chief advantages are: (1) great flexibility in combustion rates; (2) uniform feeding of the fuel and automatic removal of ash; (3) distribution of reasonably correct amount of air to each of the three zones of the fuel bed, namely, coking zone, incandescent zone and refuse zone; (4) reduction in boiler-room labor costs and greater freedom from labor troubles.

When to Install a Stoker.—It is the writer's opinion that hand-firing for bituminous coal is poor engineering practice, broadly speaking. Today there is sufficient variety in marketed stokers to suit the usual fuel, load and labor conditions in the average power plant. The problem is merely to adopt the stoker to the fuel, then design the furnace to suit the bolier, fuel and combustion rate. Some engineers argue that the office building power plant is inherently unsuited to stokers because of lack of head room and gravity coal handling. This is the architect's blunder. Conditions that do not permit of giving sufficient head room for adequately high boiler settings, and where coal cannot be conveyed in electric larries from the side-walk bunker to the stokers are indeed extraordinarily rare. In the above the author includes the hand stoker among others.

OPERATION OF CHAIN-GRATE STOKERS

The chief thing to have in mind is that the purpose of this stoker is to burn the coal completely by the time it reaches the rear or refuse end.

Adjusting the Grate Tension.—Make sure that the boiler damper is tight. Determine, and mark in a convenient place, the wide open and tightly closed damper positions. To take up slack in the chain-grate adjust the tension screws at the back

of the grate; take up until the tension is tight, then slack off slightly on both sides. The tension is usually too loose if the grate sections dip down much below the horizontal on coming over the top of the front sprocket. Lubricate all bearings well with heavy oil. See Fig. 42.

Stokers with ledge plates to keep down the excess air leakage between the side-wall and grate should be adjusted from time to time. The clearance between plate and grate should be about ⅛ in.

Feed the Coal Evenly.—If the coal does not feed in evenly, due to the coal feed hopper gate not being level, or to segregation of lumpy or fine coal, or to foreign substances in the hopper, a
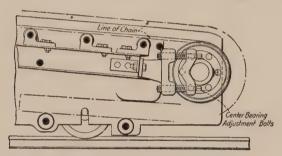
Fig. 42.—Chain take-up for chain grate stoker.

uniformly thick fuel bed cannot be maintained; the boiler efficiency, and possibly capacity, will therefore fall off.

Ventilated Arches.—These should be kept clean of all foreign matter. They cannot be cooled if dirty.

Burned and Broken Grate Links.—Excessive burning of the ends of the links indicates excessive loss of burning combustible over the refuse end, or too long links. Chronic burning of link ends is alleviated· by some engineers who redesign the links, giving them renewable ends. Broken links should, of course, be replaced as soon as possible.

Starting a Fire.—Start the water circulating through the water back, if one is provided. Remove the feed hopper plate and

cover the grate for about three-quarters its length with coal to
depth of 4 or 5 in. Cover the layer of coal with wood, shut
the dampers under the uncovered part of the grate, if dampers are
used, ignite the wood with oily waste or other combustible.
Run in more coal as needed to avoid inrush of air at the feed
hopper. When coal is burning lively all across the grate, set
the hopper plate in place, fill the hopper with coal and start the
stoker in motion at its slowest speed. Do not force the fire too
much at the start; but aim to get the arches hot without loss of
too much time, except in an installation being started for the
first time. See Fig. 43.
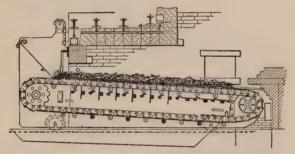
FIG. 43.—Coal and wood on grate ready to be ignited.

Speed of the Stoker.—The speed depends chiefly upon the
capacity desired, the thickness of fire carried, and the percentage
ash in the coal. The aim is too burn off all the volatile in the
coal before it reaches half the distance between the feed hopper
and the refuse end of the grate. No unconsumed combustible,
within reason, should go over the refuse or water-box end; and the
layer of ash here should offer resistance enough to avoid excess
air losses. Really the only safe way to know how to adjust the
stoker speed for given draft, load and fuel conditions is to check
operation by flue-gas analyses. The usual speed is from $2\frac{1}{2}$
ft. to $3\frac{1}{2}$ ft. per min. A high ash coal produces too thick a
layer of ash at speed below a limit varying with the ash content,
and a low ash coal will give too thin a layer at high speeds.

Fig. 44 shows effect of a fire too thin at the rear of the grate.

Keep the side-walls clean of clinker and slag by scraping it off with a bar run along the wall; be careful not to dislodge the gate tile. If partly consumed coal banks up at the water back due to heavy feeding of coal, stop feeding for a minute or so. This gives a thin strip of fire across the grate onto which the bank may fall and through which sufficient air will likely flow to
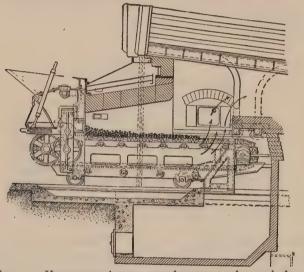
FIG. 44.—How excess air may enter furnace at refuse end of grate.

burn out the bank. The bank also may be raked or pushed down on the grate.

If the coal cakes on the surface it must be broken by a bar run along between fuel bed and grate to let the air through. Serious caking at the front of the grate may be stopped by the use of water-cooled ledge plates.

Banked Fires.—To bank the fire, first burn it short, close the damper just enough to avoid smoke, raise the gate and run in about a foot thickness of coal; let a little air flow in continuously

at the gate. The stoker should be run ahead at intervals of several hours, depending upon how fast the fire burns.

Starting from a banked fire usually requires that the fuel bed be broken on account of the coal caking. Open the damper and adjust the gate to the running position. Operate at slow speed until the coking arch becomes normally hot.

One naturally would have sense enough to watch for serious corrosion of the water-box and its connections. Some chain-grate stokers, the Laclede-Christy for example, does not use a water-box; but uses a bauxite tile.

When burning natural lignites or slack high in moisture the fuel bed, particularly at the refuse end, usually requires frequent breaking up to let the air through.

If the coking arch rapidly deteriorates at the end nearest the incandescent zone it is too long or too near the fire. Shorten or raise the arch; the horizontal tile baffle on the boiler tubes will reflect sufficient heat at this point. If the heat is still too intense bare the first row of tubes, using T-tile.

Operation of Over-feed Stokers

Characteristics of the Stoker.—The grates form steps which, in most stokers receive a to-and-fro or up-and-down motion; coal is fed by a pusher plate, by motion of the grate assisted by gravity. Ash and clinker go to the bottom or dump grate where they are dumped or crushed. A coking arch is used. See Fig. 45.

With some over-feed stokers excellent provision has been made to graduate the air supply to the respective zones—coking, incandescent and refuse. See Figs. 46 and 47.

Starting Fires on Front-feed Types.—Cover the grates with coal on which build a wood fire. Give sufficient draft to ignite the coal over the entire grate, then feed slowly either by hand operating the pusher plates or by the engine if steam is available. When the arch is normally hot speed up the stoker.

Starting Fires on Side-feed Types.—Cover the lower ends of the grates, including the crusher, with wood. Feed coal by opera-
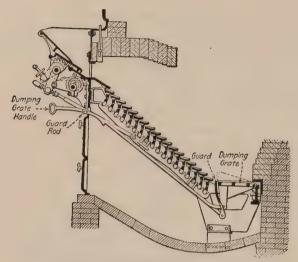
Fig. 45.—Roney overfeed stoker
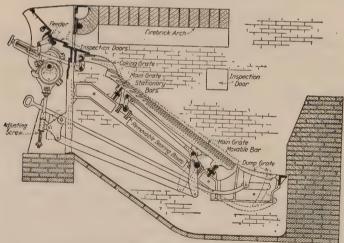
Fig. 46.—Section of Wetzel stoker; note variation in size of air openings in grate.
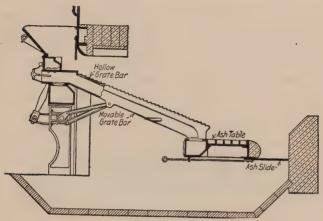
FIG. 47.—The Wilkinson stoker.
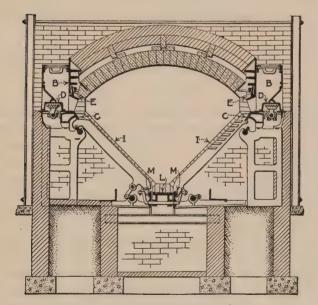
FIG. 48.—Front section Murphy stoker.

ting the pusher plate or box by hand, or power if available, to cover the grates with coal. Lay wood on the coal, ignite, and slowly feed coal after the fire is going well. Let the clinker grinder get covered with ashes before it is "hooked up" or put in operation. Keep the coal magazine filled with coal. See Fig. 48.

With either of these types of over-feed stoker, front- or side-feed, do not disturb the fuel bed with a bar unless severe clinker or caking troubles make it imperative. Such disturbance tends to cause avalanching of the fuel bed. When getting a fire started from a banked condition it is usually desirable to loosen the fuel bed with a routing bar.

Never try to crush too large or solid a clinker by jamming it with the dump grate. Break it with a bar and pull it out the door.

Speed of the Stoker.—The speed of the stoker may be varied by varying the speed of the feeder plates, grates and crusher. The speed must be varied with the load and with the volatile and ash content of the coal.

OPERATION OF SINGLE- AND MULTIPLE-RETORT UNDERFED STOKER

Operation of Underfeed Stokers.—The coal burns from the top down, the coal being supplied from beneath the fire. This causes the volatile and air for combustion to pass through the incandescent zone which breaks up the heavy tars and other volatiles. As forced draft is used the air supply is sufficient to quite completely burn the tars, and what little soot may form, at the surface of the fuel bed. The principle of the stoker is a close approach to the ideal.

Jones Stoker.—See Fig. 49. Coal falls into a retort where it is pushed ahead by a steam-operated ram. The fire burns from the top down. An engine-driven fan regulated by the steam pressure furnishes air for combustion, the air entering hollow tile tuyère blocks located along the retort and working its way up through the fuel bed. The coal cokes in the front part of the

open top retort.   The retorts are 6 ft. long, 28 in. wide and about
18 in. deep, the depth decreasing from front to rear to give the coal
an upward movement as it is fed in.

Feeding the Coal.—The stroke of the ram or pusher rod may
be varied by means of straps and holes, so that the opening
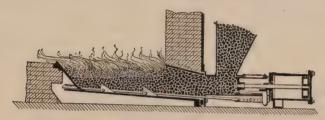
FIG. 49.—Section of Jones stoker.

between the ram and bottom of the feed hopper may be greater
or less, according to the amount of coal it is desirable to permit to
enter the retort at each stroke.   An automatic device is pro-
vided for varying the rate of feeding coal; it is graduated as
shown, has an index, and the rate of feeding is increased accord-
ing as the index is set at numbers
from o to 8, and decreased as set from
8 to o.   Ordinarily, keep a heavy fire,
say 20 to 24 in. thick.   Fig. 50 shows
the automatic control valve.

Starting the Fire.—Fill the retort
with coal by shoveling it in through
the doors in the boiler front; cover
the tuyère blocks.   On top of the coal
start a wood fire, using natural draft.
When the steam pressure is 40 lb. use

FIG. 50.—Control valve,
Jones stoker.

it to operate the ram; the ram may be operated by hand by
means of a lever.

If steam from other boilers is available, use it to fill the retort
when starting a new fire.   Throw live coals from another furnace
along the sides of the retort and on the coal over and alongside

the tuyère block, also throw live coal on the coal in the retort. Start the fan slowly and bring the fire up slowly.

Cleaning Fires.—Too great an accumulation of ash causes clinker trouble. If clinker forms, break it by lifting it with a bar, dump the live coals to one side and pull the clinker out of the furnace. The dead plates and tuyère blocks only need be cleaned of ash and clinker.

To Bank the Fire.—Feed several charges of coal and cut off the draft. Take care when about to start from a banked fire to see
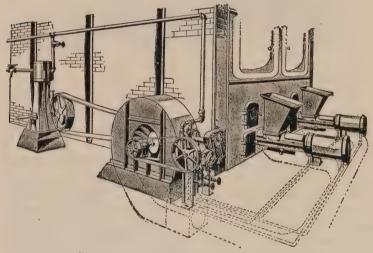
FIG. 51.—Typical installation of Jones stokers.

that the coal in the front of the retort is not seriously caked; if caked break it up before starting the ram.

Be most careful to keep out of the retort sticks, pieces of chain, etc., that come in coal from the mines. Obviously it is unwise to neglect lubrication of the cylinder, automatic feed valve, engine and fan. Fig. 51 shows typical installation of Jones stokers.

Fuels for the Jones Stoker.—The Jones stoker has indeed been successful in handling all grades of bituminous coal and in burning coal and waste fuels, such as hog feed or paper mill refuse.

Its wide use all over the country is indicative of its adaptability to various fuels. See Fig. 4, page 217, for boiler setting for burning solid refuse fuels with this stoker. Fig. 52 shows section of type E stoker.

Operating the Underfeed Stoker.—The following general directions are, in part, those given by the Westinghouse Electric & Mfg. Co., and apply particularly to the Westinghouse stoker; but generally they apply to any multiple retort stoker. No definite operating rules can be given on account of the different characteristics of the coal that may be burned on the stoker and the load
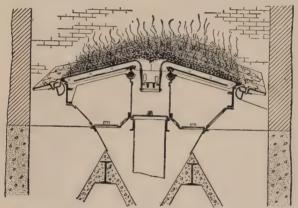
FIG. 52.—Front section type E stoker.

or capacity demands that may be imposed on the stoker. Therefore, the successful operation of the stoker resolves itself into a matter of common sense while observing fundamental rules. Fig. 53 shows section of Westinghouse stoker.

Starting Fires.—First inspect all moving parts to see that they are free from objects which would obstruct their movements; start the stoker and let it make a few revolutions of the crank-shaft, then fill the hopper with coal and push in a sufficient amount to cover the tuyères with about 8 or 9 in. of the coal. If there is no steam available to run the stoker engine, coal should

be shoveled in by hand and evenly distributed over the underfeed section. Light a fire on top of the coal and close to the front

Fig. 53.—Westinghouse underfeed stoker

wall, with wood. After the wood is ignited a light air pressure can be used to quickly ignite the coal, or natural draft may be used by opening the wind-box doors in front of the stoker. After

sufficient ash has accumulated to protect the tuyères, the moving and dumping grate sections, the stoker may be put in regular service. Unless absolutely necessary, do not force the stoker until the fuel bed is in a good coked condition and the fuel is evenly distributed over the entire grate. Fig. 54 shows the relation between pounds of dry coal per retort and static pressure in the wind box. Fig. 55 shows the relations between the
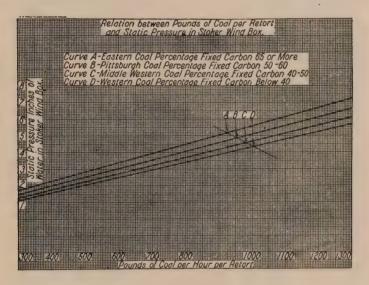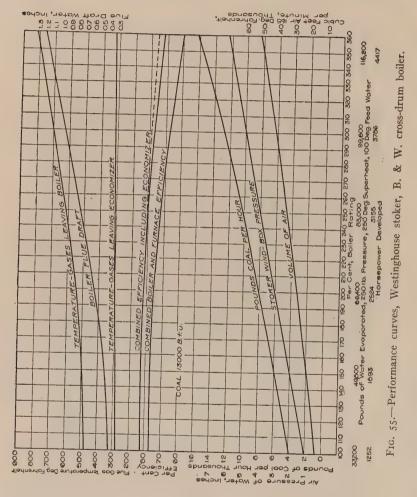
FIG. 54.—Relation between coal burned per retort per hour and static pressure in stoker wind box.

coal burned per hour and the other factors of stoker performance.

Each feeding ram will displace from 13 to 18 lb. of coal per stroke. The approximate weights are 13 lb. for lignite; 16 lb. for Western coal and 18 lb. for Eastern coal. Fig. 56 shows the relation between speed of crank-shaft and coal fed per retort per hour. With little attention and observation the proper relation of coal and air pressure required may be determined by the fire and fuel-bed conditions.

Furnace Draft.—Keep the draft over the fire between 0.10 in. and 0.25 in. water gage; this can be obtained by proper manipu-

FIG. 55.—Performance curves, Westinghouse stoker, B. & W. cross-drum boiler.

lation of the flue and stack damper alone, or in conjunction with the stoker wind-box damper. The damper control levers or mechanism should be located at the boiler front.

Size of Coal.—The best size of fuel is that having the largest percentage crushed to about ¾-in. cubes, the maximum size being 1½-in. cubes. Distribute the coal evenly in the stoker hoppers. This is very important to successful operation. It is often advisable to moisten screenings if they are very dry; this also applies to non-caking coals.
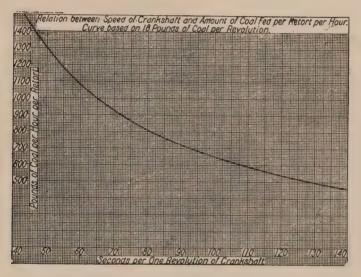
Fɪɢ. 56.—Relation between speed of crankshaft and coal fed per retort per hour.

Some coals of the Middle-West including lignite tend to clog in the hoppers and retorts due to their high moisture content. It is important that a continuous feed is maintained in each retort.

It is advisable here to say that the writer believes that much of the shearing of connecting rod pins and breaking of stoker parts is due to improper care on the part of the operator when trying to relieve a clogged retort. Just reason it out: Coal swells on becoming hot and coking. If the stoker is stopped for any length of time when the furnace temperature is high, the coal in and ahead of the retort cokes, swells and, as there is no

movement of the rams, sticks. It will form quite a hard mass which strongly resists the movement of the ram. Do not try to dislodge this mass by feeding a full retort of coal in front of the ram. When this is done one tries to push the coked mass ahead at once a distance equal to a full retort length. Try to get only a little coal ahead of the ram, gradually increasing the amount as the coked mass is broken. The formation of such a mass may be avoided generally by turning the stoker a revolution once in awhile, breaking it up as it forms.

Outline of the Fuel Bed.—The outline of the fuel bed has considerable influence on the capacity and efficiency of the boiler and stoker. Fig. 53 shows the correct and incorrect outline of the fuel bed. A heavy fire decreases both capacity and efficiency, especially if the rear end of the fuel bed is heavy and the front end is light. This condition induces serious clinker trouble as the green fuel will fuse with the ash and clinker to the bridge-wall, making it troublesome to dump the ashes. If the fire is carried too light, losses occur due to excess air.

Care should be taken in connection with very wide stokers that the fuel bed is kept evenly thick across the entire length. If one side is heavier than the other, the clutches on speed shafts operating cranks on that side should be released and the coal feed continued on the light side.

Sections of the Riley and Taylor stokers are shown in Figs. 57 and 58 respectively.

At the points where the connecting rods engage the ram yokes are nuts which may be adjusted to vary the lost motion to suit the characteristics of the coal. If, however, it should be found desirable to adjust the length of the stroke of the secondary rams when the stoker is in operation, additional movement of 1 in. may be obtained by placing U-collars on the lost motion connection engaging the connecting rod pins of the main ram. Unless there is a radical change in quality of the coal used, the secondary rams do not require additional adjustments. Precaution should be taken that the U-collars are placed and removed simultaneously for each retort so that the strain on the connecting rod pin and
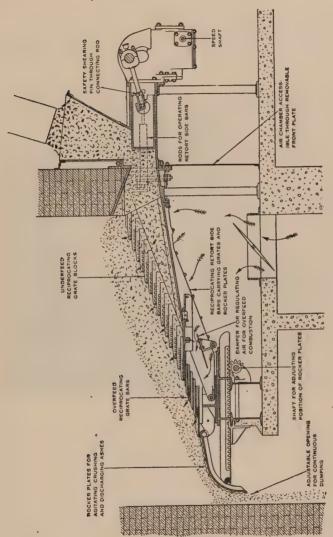
FIG. 57.—Section of Riley underfeed stoker.

the yoke is equalized. The reciprocating movement of the moving grates is adjusted in a similar way.

As a general rule, coals obtainable in the East do not need motion imparted to the moving grates. The adjustments refer particularly to high ash coals of the Middle West.
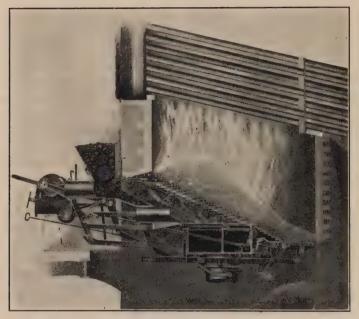
FIG. 58.—Taylor underfeed stoker.

Damper Adjustment.—With certain coals it may be found desirable to have the bridge-wall dampers partly open all the time. If so, provide a stop so the damper cannot be entirely closed. This precaution should be taken where there is excessive clinker formation on the bridge-wall and where the grate bars of the surface of the dumping grates burn away.

Dumping and Cleaning Periods.—The dumping periods depend upon the amount of ash in the coal. To keep the fuel loss to the ashpit down admit air to the dumping grates before

cleaning sufficiently long to burn out most of the carbon in the ash. Break up the clinker if it is in very large pieces so the air can get at the greatest surface in the least time.

Spray the ashes as soon as they are dumped. Few things are so much appreciated as a large ashpit or ash hopper.

The side-walls should be cleaned of clinker at least once every 24 hr. during periods of light load or bank by burning the fire relatively thin. The formation due to cooling will then be easy to dislodge. A slice bar of tool steel $1\frac{1}{2}$ in. in diameter and approximately 12 ft. long, one end formed to a blade 12 in. long and 4 in. wide, is suitable. If the bar is bent to form the arc of a large circle it may be used to effectively wedge the clinker from the side-wall by simply pushing it ahead.

Blow the front working parts of the stoker with compressed air or steam to keep them clean.

Lubrication.—Fill the gear case with a mixture of thick oil and graphite. The oil should always be 1 in. above the oil hole in power-shaft end bearing; it will then cover all holes provided for lubrication.

Drain the gear box occasionally and wash it out with kerosene. Of course, one should not negect the lubrication of the crankshaft bearings, connecting rods and clutch.

Keep the driving chains protected from dust; brush them when dusty and wash out the heavy grease and dust with kerosene, after which oil well by immersing in heavy oil.

For adjustments to the stoker engine the user will find it worth while to obtain the maker's literature on the subject.

Cleaning the Fan Blades.—It is important to keep the blades of the forced draft fan clean of dirt. This may be done by blowing the blades with steam or compressed air, steam is best.

Fire in the Wind Box.—If the coal cokes and clogs in the retorts of some underfeed stokers, continued running may cause live coal to get into the wind box where, continuing to burn, it will melt the box. Watch for this trouble. Should it happen, play water from a hose upon the red-hot spot of the wind box, and let it run there until the coked mass is cleared away and the
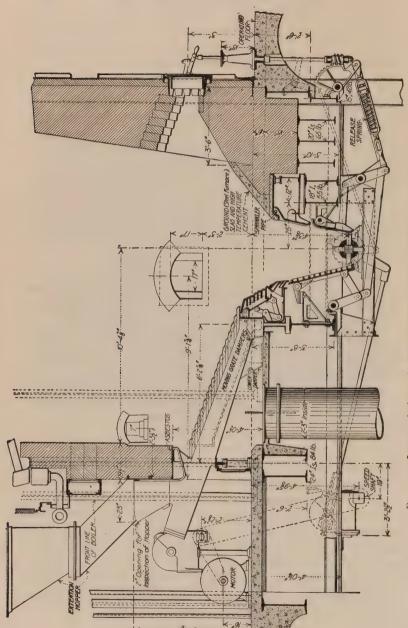
Fig. 59.—Latest design of Westinghouse rotary clinker grinder—1918.

fuel bed is again normal. This removes the cause of the coal getting into the wind box.

Exert every effort to keep sticks, pieces of chain and other foreign substance out of the coal fed to the stoker hopper.

Clinker Grinders.—Clinker grinders are used in but a few of the large power stations at this writing. Their use will likely become far more general. They should be kept cool, and those provided with sprinkler pipes should give little trouble if these pipes are kept open and allowed to function properly. Little is known of their operation; but if kept cool, the writer sees no reason why they should give any trouble, and why they should not be a paying investment.

Water cooled clinker grinders of present-day design require about as much water as the boiler evaporates in the same unit of time. There seems no reason why water from the hot wells of surface condensers, *i.e.*, the condensate, could not be circulated through the clinker grinder water back before being fed to the boiler or to other feed-water heaters. Fig. 59, page 288, shows one of the most recently designed clinker grinders.

CHAPTER VIII

ECONOMICAL BOILER RATINGS

Among many operating engineers the mistaken idea prevails that it is *always* economical to force boilers above their rated capacity. This is likely due to the wide publicity given to high boiler ratings as practised in central power stations and plants having similar load characteristics. In these plants the combined boiler and furnace efficiency drops as the boiler is forced beyond normal rating; but because the load on the boilers swings for periods of a few minues to a few hours considerable above the average load, it becomes more economical, as based on over-all cost per unit of output, to run the boilers at anything up to 500 per cent. builders' rating for these overload or peak load periods. Otherwise it would be necessary to install more boilers, run them all at inefficiently low rates during off-peak periods or, bank some of them during such periods. The loss due to running at low rating or to banked fires, and to overhead on the excess number of boilers would be greater, in the average plant, than the loss due to operating fewer boilers at high ratings for comparatively short periods. Like every other engineering success, we must find the most economical point of compromise between two extreme conditions. Have in mind that the economizer very greatly off-sets the loss due to high boiler ratings.

By far the greatest number of tests of hand-fired boilers shows that for nearly all, if not all, coals, the highest combined efficiency is had between 70 and 90 per cent. of builders' rating.

The modern water-tube boiler set to give large combustion volume and fired by multiple retort underfeed stokers shows an astonishingly flat efficiency curve for a wide range of forcing above builders' rating. The curve, Fig. 55, well illustrates this fact.

Stoker and Economizer Revolutionize Boiler Ratings.—The underfeed stoker particularly, and the economizer, revolutionize economical boiler ratings. The character of the fuel bed of the underfeed stoker gives such thorough mixture of air and combustible gases in the fuel bed and beyond that high combustion rates are possible without serious efficiency losses. If the economizer is used in addition then much of the heat otherwise carried up the chimney, due to the increased combustion rates, is absorbed by the feed water and restored to the boiler.

The top curve, Fig. 55, shows the typical increase in flue-gas temperature for increase in the combustion rate or boiler rating. The increase here is as follows:

Per cent. boiler rating	Flue-gas temperature, deg. F.
100	470
150	520
175	550
200	575
250	630
275	655
300	680
350	740

The specific heat of flue gas is 0.24 B.t.u. per lb. The economizer will ordinarily absorb 3.5 B.t.u. per sq. ft. per hr. per degree mean temperature difference between inlet and outlet of gases. It is readily realized, therefore, that the economizer is essential to economy if the boilers are operated continuously in the region of high flue-gas temperatures. But there must be sufficient volume of gases passing to make the economizer a paying investment, and this is determined, with accuracy sufficient to move one to invest money, only by the conditions of each installation for which the economizer is proposed.

Steel Economizers.—Sargent and Lundy, consulting engineers, Chicago, are now designing high pressure steam plants which will use cast-iron economizers under about 100 lb. pressure, the feed

water going from this economizer to one constructed of steel drums and steel tubes under boiler pressure.   They hold promise; but it is too soon, at this writing, to tell how commercially successful they will prove to be.

Influence of Combustion Rates on Efficiency.—With the tendency toward high combustion rates the effect of combustion
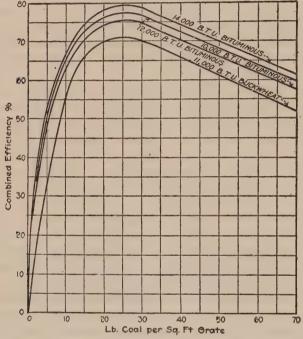
Fig. 60.—Relation between combined efficiency and coal burned per hour per square foot of grate.

rate on combined efficiency with various coals becomes of increasing importance.   The following curves, plotted from tests in the plants of the Public Service Electric Co., Newark, N. J., and presented by Joseph T. Foster in *Power*, Apr. 23, 1918, are interesting:

Boiler tests prove that the plotting of combined efficiency

against the pounds of coal burned per square foot of grate surface shows a characteristic curve which has a definite form regardless of the character of the fuel or the size of the boiler. Fig. 60 shows the form of curves derived from actual tests. The curves for bituminous coal were obtained from tests on a battery of 1400 rated horsepower boilers and the curve for the buckwheat is a composite from numerous tests on boilers varying in capacity from 1000 to 250 hp. It will be noticed that the curves have the same general characteristics even though boiler capacities and kind of fuel varied widely. All grades show best efficiency at a rate of about 25 lb. of coal per square foot of grate surface
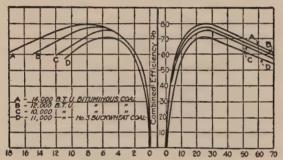
FIG. 61.—Combined efficiency at various stoker forcing rates.

per hour. Boiler-heating surface seems to have been pretty definitely fixed at 10 sq. ft. per nominal horsepower, and on this basis the curve will be of value in predicting efficiencies at various forcing rates.

Fig. 61 is a combined curve showing efficiencies plotted against pounds of coal per square foot of grate per hour and boiler horse-power per square foot of grate. The effect of the burning qualities of the fuel on the output is very marked. The most economical forcing rate for the 14,000-B.t.u. coal is 9 boiler horsepower per square foot of grate and for the buckwheat 6 hp. There is also a difference of approximately 10 per cent. between the best efficiencies realized.

Fig. 62 is a chart worked out on the basis of test results and shows the relation between combined efficiency and grate surface for various sizes of boilers under different operating conditions and with different kinds of fuel.

Example 1.—What efficiency will be obtainable with a 1400-hp. boiler having 290 sq. ft. of grate surface when operated at 200 per cent. rating with 14,000-B.t.u. coal?

Solution.—Project upward from 290 sq. ft. of grate surface to the 200 per cent. rating line, then horizontally to the right
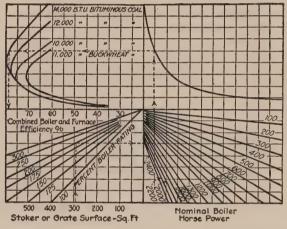
FIG. 62 —Relation of boiler horsepower, per cent. rating, grate surface and efficiency.

to the 1400 nominal horsepower line, then vertically to the curved transfer line and horizontally to the left to the point of intersection with the efficiency curve, thence vertically downward, read the efficiency as 78.5 per cent.

Example 2.—A boiler with a nominal rating of 1000 hp. and having 350 sq. ft. of grate surface is being operated at 150 per cent. rating on 12,000-B.t.u. coal. Is it developing its best efficiency, and if not, at what rating should it be run?

Solution.—Following out the method outlined, it will be seen that the boiler is developing 73.5 per cent. efficiency. The best

efficiency with this coal is 77.5 per cent. Reversing the operation by projecting horizontally from the point of best efficiency of the curve for 12,000-B.t.u. coal to the transfer line, downward to the nominal rating curve, horizontally to a vertical line from 350 sq. ft., read 230 per cent. as the rating at which to operate the boiler for maximum efficiency. Where a number of boilers are on the line operating under the conditions in the second
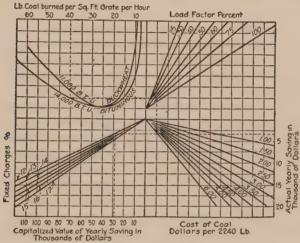
Fig. 63.—Capitalized value of saving realized by operating at best forcing rate.

example, it would be possible to cut out one or more boilers with a large fuel saving on account of the increased efficiency of the remaining boilers at the higher rate of steaming.

The practical use of this method will be recognized and the following instance is a case in point: The initial installation in a certain plant consisted of a battery of boilers with 221 sq. ft. of grate surface and rated at 1400 hp. and operated at 79 per cent. efficiency when developing 145 per cent. rating, burning 14,000-B.t.u. coal. Increased load on the plant required a second installation, and it was desirable that it should develop its best efficiency at a higher rating. It was therefore designed with a

grate surface of 291 sq. ft. and will develop 79 per cent. efficiency at approximately 200 per cent. rating. It is much cheaper to develop greater horsepower by means of larger grates than by increasing the boiler-heating surface, for large heating surface involves high initial cost not only of the boilers themselves, but of all the other items entering into their erection. Where cubic feet of available space in the boiler house is limited, the question of grate surface is of importance because every unnecessary cubic foot taken up by the boilers means a higher plant cost. The question of grate area, however, is not limited to new plants, but is of equal importance where boilers are already installed. Where the grate surface is found to be too small, it would be profitable in almost every instance to spend the money necessary to enlarge it.

Fig. 63 is designed to show in dollars the saving which will result from changing from a given condition to the best condition, as shown in Fig. 63; namely, 25 lb. of coal burned per square foot of grate per hour, for various load factors and coal prices. The value of the annual saving, capitalized at from 12 to 17 per cent., is also given. All values are calculated for a 1000-hp. load, the data for other loads being proportionate. Only two grades of coal are shown in this chart, but other grades, since they fall between the two, can readily be allowed for.

Combustible in the Ash when Forcing Boilers.—With all underfeed stokers it is always possible to feed too much coal for the load to be carried. This creates a thickened or heavier than usual fuel bed, which tends to shut off the air supply to the fuel bed. The result is that the faster the coal is fed by the stoker the greater the amount of carbon or combustible which reaches the dump grate or refuse end of the stoker. Without controlled air admission at this point, together with means of agitating the clinker so as to expose the combustible to the air the loss of combustible will increase with the rate of combustion, or more correctly, with the rate of feeding coal. At high rates of forcing the combustible in the ash runs as high as 40 and 50 per cent., the total weight of ash or refuse discharged

taken as 100 per cent. All builders of multiple retort underfeed stokers are at this writing taking steps to cut down these losses, a rotary ash discharge (clinker grinder) coming into general use as a result. Fig. 59 shows one of the latest designs of clinker grinder developed by the Westinghouse Electric & Mfg. Co.

The action of the fuel bed and air supply when forcing boilers was well set forth by Victor B. Phillips of the Cleveland Railway Co. in a paper, "Relation of Efficiency to Capacity in Boiler Rooms," Spring Meeting, American Society of Mechanical Engineers, Cincinnati, Ohio, May, 1917:

The effect of fuel-bed thickness upon furnace efficiency is most marked for the light loads and least marked for the heavy loads. With a thin fuel bed, a drop in efficiency characterizes heavy overloading. With heavy fuel bed the reverse is true. The explanation of all this lies primarily in the air supply and distribution.

The data are self-evident in showing an insufficiency of air for all loads in the case of the heavy fuel bed. Obviously, at light loads the thick bed shuts off the air most effectively. However, the key to these peculiar characteristics is to be found in the air supply to the lower extension and dump grates. Quite regardless of the fuel-bed thickness, overloading is accompanied by a piling up of unburned coke on these grates. The grates are designed for rated load, and for rated load the air supply is sufficient. The extension grates are supplied with air from a chamber opening through slide valves into the main-grate air boxes. Hence, any regulation of the main air supply affects proportionally the extension-grate air supply.

The stoker also depends, to some extent, on the air drawn up through the dump grates by the small draft carried in the furnace. When the boiler is overloaded it becomes necessary to increase proportionately the combustion rates and, therefore, the air supply on all sections of the grate surface. This applies just as much to the extension and dump grates as to the main grates. However, due to both an insufficient and an almost inflexible air supply on these lower grates, combustible is delivered from

the upper or main grates much faster than it can be burned on the lower grates. The result has been indicated. The piling up of ash and combustible rapidly makes worse the insufficiency of air. The losses from CO and the combustible to the ashpit increase excessively, and the net results are low efficiency and a tendency to the formation of clinker. The gas-analysis charts show that almost all the CO is formed on these lower grates. The CO begins at a low value just after cleaning and increases as the piling up of combustible increases.

It should be noted that this discussion applies specifically to the air supply and distribution. This Taylor stoker did not have a controlled air supply with pressure to the dumping grates.

The following figures are from tests of a Westinghouse double dump grate stoker at the Union Electric Light & Power Co.'s plant, St. Louis. The coal contained from 16 to 22 per cent. ash. The value of controlled air admission to the dump grates is forcibly shown by these tests.

Boiler rating, per cent.	Combustible in ash, per cent.	Ash in coal, per cent.
169.7	18.0	15.9
154.0	11.5	18.3
217.65	....	19.8
153.78	9.5	18.2
174.5	7.5	18.38
176.0	11.5	22.2
165.0	14.0	20.7
159.0	23.0	20.7
170.0	16.0	20.7
164.0	14.0	20.4
170.0	11.2	20.5
189.6	15.0	19.9
178.0	15.0	18.2
116.0	14.0	20.2

Tests of the stoker having the clinker grinder shown in Fig. 59 gave as low as 8 per cent. combustible in the ash up to over

250 per cent. rating. The coal is an Eastern coal averaging 7 per cent. ash.

Feeding Water to the Boiler.—With boilers subject to fluctuating loads, and particularly where they are periodically forced, the rate at which feed water is injected into the boiler should, in nearly every plant, be varied to anticipate heavy demands for steam, *i.e.*, fill the boiler to maximum water level during periods of light load and reduce the rate to a minimum during heavy loads. This gives minimum interference with the steam flow. Some feed-water regulators perform this function automatically.

Effect of Feed-water Temperature and Rate of Feeding upon Steam Flow.—(Frank G. Philo, *Power*, 1918.)

Under any given condition the actual output of the boiler expressed as B.t.u. absorbed per unit of time is constant, regardless of the rate and temperature at which the feed water is injected. However, boiler output expressed in pounds of steam per unit of time varies widely with changing feed-water temperature and rate of feed-water injection, being highest when no water is being fed to the boiler and lowest when the feed-water temperature is very low and the water is injected at a high rate.

When the feed water is fed into the boiler at the same rate at which the boiler is steaming, the normal condition will be considered to exist and the amount of water in the boiler will be constant. Any rate of feed-water injection above or below normal will increase or decrease the rate of boiler steaming and the amount of water in the boiler. Shutting off completely the supply of feed water will appreciably increase the rate of steam flow. On the other hand, any increase above the normal rate of feed-water injection will reduce the rate of steam flow; in fact, if the water is fed fast enough, steam flow will cease entirely. A still greater rate of injection will cause a reversal of steam flow from the line if the boiler is not equipped with nonreturn valves. If nonreturn valves are used, the pressure on the boiler being fed at this abnormally high rate will drop below line pressure.

The aforementioned effects are most noticeable when very cold water is used and when the rate of steaming is low.

An interesting example of the reverse effect of temperature of feed water is in cases where economizers are used and the tem-
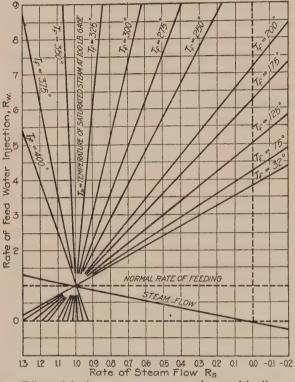
FIG. 64.—Effect of feedwater temperature and rate of feeding upon steam flow.

perature of the feed water is equal to or greater than, in some cases, the temperature of water in the boiler. When the feed temperature is the same as the temperature of the water in the boiler, feed-water injection does not affect the rate of steaming. When the feed water is actually higher in

temperature than that in the boiler, an increase in steam flow occurs upon feeding water into the boiler.

The following formulas and the chart, Fig. 64, show the magnitude of the foregoing effects.

H = Total heat above feed-water temperature of 1 lb. of steam;

L = Latent heat of 1 lb. of steam under given conditions plus B.t.u. for superheating 1 lb. of steam (if superheated):

h = Heat of feed water from feed temperature to boiler temperature;

R_s = Rate of steaming;

R_w = Rate of feed-water injection.

1. With feed water shut off entirely, $R_s = \dfrac{H}{L} = 1 + \dfrac{h}{L}$.

2. The rate of feed-water injection that would decrease steam flow to the rate R_s would be $R_w = 1 + \dfrac{L - R_s L}{h}$.

3. The rate of feed-water injection that would cause steam flow to cease, $R_w = 1 + \dfrac{L}{h}$. (R_s = zero.)

4. Under any given condition the sum of the heat absorbed by the feed water and the heat used in boiling the water equals the total heat, or H absorbed by the boiler. As a formula this would be written $R_s L + R_w h = H$.

For examples of the foregoing take the conditions of 100-lb. gage, saturated steam, and 60 deg. F. feed-water temperature. Then $H = 1189 - (60 - 32) = 1161$ B.t.u.; $L = 880$ B.t.u.; and $h = 281$ B.t.u.

1. $R_s = \dfrac{H}{L} = \dfrac{1161}{880} = 1.32$, the rate of steaming with no feed.

2. Let $R_s = 50$ per cent., then $R_w = 1 + \dfrac{L - R_s L}{h} = 1 + \dfrac{880 - (0.5 \times 880)}{281} = 2.57$, the rate of feed required to reduce the rate of steam flow to 50 per cent. of normal.

3. $R_w = 1 + \dfrac{L}{h} = 1 + \dfrac{880}{281} = 4.13$, the rate of feed required to stop steam flow.

As shown by the chart, variable feed-water injection with a steady load is disastrous to uniform steam pressure. Variable steam pressure, in turn, causes juggling of fires and short periods of loafing with consequent loss in efficiency of boilers and auxiliaries. However, with loads that have a periodic fluctuation, as in rolling mills, variable feed-water injection, if properly handled, aids the maintenance of the steam pressure. When the load is high the feed is decreased, and as the load drops the feed is increased, utilizing the heat absorbed by the boiler and admitting of fairly constant furnace conditions. This condenser action or heat-storage effect of the feed water is quite appreciable and is taken advantage of by intelligent water tenders. The matter of correct boiler feeding in the majority of cases is not given the attention it deserves, as the results of improved methods of boiler feeding are felt in the operation of the whole station as well as in the coal pile.

INDEX

Tar, gas, heating value, 198
    formation of, in boiler furnaces,
      206
Temperature, absolute, 87
    of flue gas, measuring, 79
Thermometer, chemical, 33
Titrating, 166

Ultimate analysis, 22

Volatile, definition, 23
    combustion volume as related
      to, 210–212
    distillation of, in coal, 200
      when stoker fired, 205

Volatile, in dry coal, 39
    in typical American coals, 190–
      196

Water, alkalinity, 167
    boiling temperatures, 104
    burette for measuring, 165
    collecting samples, 167
    common impurities in, 156
    feed, treatment, 155
      rate of injection as it effects
        steam flow, 299
    indicators for analyzing, 166
    proximate analysis, 163
    testing treated, 171
Weight, combining, of elements, 12